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EVALUATION OF THE IMPACT OF TOWING THE L-1011 AIRPLANE AT BOSTON-LOGAN AIRPORT

12 LEVEL II

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16. Abstract

Results of a research program to determine the impact of towing transport airplanes at Boston-Logan Airport are presented. The study includes the measurement of actual towing loads during airline operations with the L-1011 at Los Angeles International Airport (LAX) and Dorval, Quebec (YUL). The measured towing loads were obtained with an instrumented towbar and portable data recording package. Towing loads were also measured during controlled test conditions at Palmdale using the flight-test L-1011 airplane. A fatigue load spectrum representing ground maneuvering including the effects of extended towing was developed. Stress analysis of the nose landing gear and back-up structure was performed using the load spectrum representing extended towing at Boston-Logan. The results indicate that the proposed extended towing operations do not cause a reduction of fatigue life of the nose gear to below the design life for the L-1011. A discussion of alternate towing concepts is presented, and limiting conditions are defined to ensure acceptable operational safety during extended towing.

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FOREWORD

This report was prepared by the Lockheed-California Company under FAA Contract DOT-FA78WA-4199. The work was performed under the direction of the Federal Aviation Administration with H. Spicer and V.G. Sanborn as Technical Monitors.

The project leader was Max Gamon of the Lockheed-California Company. The following Lockheed-California Company personnel assisted in the program:

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The Lockheed effort was supervised by J.E. Wignot (Dynamics and Vibration Group) under the management of A.F. Messina (Flutter and Dynamics Department) and R.F. O'Connell (Aeromechanics Division). The author gratefully acknowledges the cooperation and assistance of TWA and Air Canada in obtaining actual operational towing loads measurements.

SUMMARY

The purpose of this program is to determine the impact of proposed extended towing operations at Boston-Logan Airport. The proposed extended towing (with airplane engines shut down) is in the Southwest Terminal region, for the purpose of noise abatement. The program includes the measurement of actual operational towing loads during airline operations with the L-1011 at Los Angeles International (LAX) and Dorval, Quebec (YUL). The latter testing was performed during February 1979 to obtain towing load data under conditions of snow and ice on the runway. The measured towing loads were obtained with an instrumented towbar and portable data recording package. Towing loads were also measured during controlled test conditions at Palmdale using the flight-test L-1011 airplane. A small computer program was developed to model the dynamic behavior of the airplane/tug combination during towing.

The test and analytical program results were used to define a fatigue load spectrum for the L-1011 nose gear representing extended towing at Boston-Logan Airport. The nose gear and supporting structure were then analyzed to determine the fatigue life with extended towing. The basic L-1011 design fatigue load spectrum was used as a basepoint for the analysis, with the original towing load spectrum replaced by the spectrum representing extended towing. The original design was sufficiently conservative that the fatigue life of all the nose gear structure remains above the design fatigue life, even with full-time enforcement of extended towing at Boston-Logan.

The fatigue damage due to extended towing operations is affected by the airplane gross weight, driver technique, tow vehicle transmission characteristics and the number of start/stop cycles during towing. Of these factors, only the airplane gross weight is readily measured and controlled. The airplane gross weight limit for the L-1011 at which extended towing reduces the fatigue life of the critical nose gear structure to the design life is

above any currently contemplated maximum airplane gross weights. For the safety of the extended towing operations, it appears advisable to establish speed limits for towing in the Southwest Terminal region. Based on the results of the towing tests, speed limits of around 12 mph for dry pavement and 9 mph for rain or snow/ice conditions (with tug chains) are indicated.

The cost penalty associated with extended towing at Boston-Logan is estimated to be less than $11 per flight. This cost results from the longer time required for towing compared to conventional taxiing; the increased crew time costs exceed the cost savings from reduced airplane fuel consumption. Various alternate towing concepts were investigated, but none appeared to be economically feasible in light of the moderate economic penalty for extended towing.

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SECTION 1

INTRODUCTION

The Massachusetts Port Authority has adopted a set of airport operating rules and regulations which, when fully implemented and enforced, will prohibit self-propelled aircraft operating movements within the Southwest Terminal apron and taxiway area at Logan Airport. This rule means that departing airplanes must be towed from the Southwest Terminal area to a point opposite the South Terminal with engines shut down and arriving airplanes must similarly be towed from the same point back to the terminal, with engines shut down. The purpose of this rule is to reduce the noise exposure in nearby residential areas.

One potential problem associated with this operation is the impact of the extended towing operations on the fatigue life of the nose landing gear and support structure. Towing the long distances and high frequencies proposed at Logan could substantially increase the towing load portion of the nose landing gear fatigue load spectrum. Whether or not this increase would, in turn, significantly reduce the fatigue life of the nose landing gear is one question to be answered by this study. Another concern about such extensive towing operations is whether the safety of the ground movements is on a par with conventional taxing under airplane power, and what operating procedures and limitations may be required to guarantee the required level of safety.

In Reference 1, the financial impact of full-scale extended towing to and from the runways at LAX was examined. The authors of that report concluded that a net cost savings is possible, with the added crew costs due to the slower towing operation being more than compensated for by the savings in airplane fuel costs with the engines off during the towing. Various companies interested in developing and selling rather elaborate aircraft ground movement systems have also expressed the opinion that extended towing can result in a cost savings. In the present study, the primary concern is with the potential fatigue damage to the nose gear structure and with the safety of extended towing. However, the cost impact of extended towing at Boston-Logan is also examined.

The program is carried out in 6 tasks. In Task I towing loads are measured on the L-1011 during actual operational and maintenance towing by Trans World Airlines (TWA) at Los Angeles International Airport (LAX), and during a controlled test program at Palmdale Airport using the flight test L-1011. A standard L-1011 towbar was instrumented with strain gages, and a portable data recording package was developed. In addition, a small computer program for predicting dynamic towing loads was developed. During Task VI, towing loads measurement were taken for Air Canada's operations with the L-1011 at Dorval, Quebec (YUL). These measurements were made during February to determine the effect of snow/ice surface conditions on towing loads.

The towing loads measurements and analytical results are used in Task II to formulate a fatigue load spectrum representative of the extended towing operations at Boston-Logan. In Task III, the extended towing load spectrum is analyzed to determine its effect on the predicted fatigue life of the nose loading gear and supporting structure.

Alternate towing concepts are presented in Task IV, and an estimate of the cost impact of extended towing is developed. Conditions which limit the acceptability of extended towing at Boston-Logan are established in Task V, both in terms of fatigue damage to the nose gear and the safety of the extended towing operation.

SECTION 2

TOWING LOADS TEST PROGRAM

The objective of the test program is to de.ermine the magnitude, frequency and dynamic characteristics of current in-service towing loads for the L-1011, as well as the towing loads under controlled test conditions using the flight test L-1011 airplane at Lockheed's Palmdale facility. With the cooperation of TWA and Air Canada, operational towing loads were measured at LAX and Dorval, Quebec.

2.1 TOWING LOADS INSTRUMENTATION

Since one of the objectives of the test program is to measure actual in-service towing loads, a primary requirement for the instrumentation system is that it not delay the normal airplane ground-movement procedures. This requirement precluded any direct measurement of nose gear loads, such as by utilizing strain gages on the nose gear. The instrumentation system developed consists of a standard L-1011 towbar (Wollard Model TB-571-C) with strain gages mounted on the main tube to measure axial load and lateral bending moment, a nose-wheel speed sensor attached to the towbar, a steering angle transducer attached to the nose gear and a recording package that rests on the tow vehicle.

Figure 2-1 shows an overall view of the nose gear, strain-gaged towbar and the instrumentation package resting on the tow vehicle. Figure 2-2 is a closeup view of the instrumentation package showing the arrangment of the principal elements. The tape-recorder uses 4-track cassette tape with the recording done in the FM mode. The four response-histories recorded are towbar axial load, towbar lateral bending moment, nose wheel speed and nose gear steering angle. The signal conditioner processes the strain gage signals from the towbar, and provides calibration signal levels. The battery pack

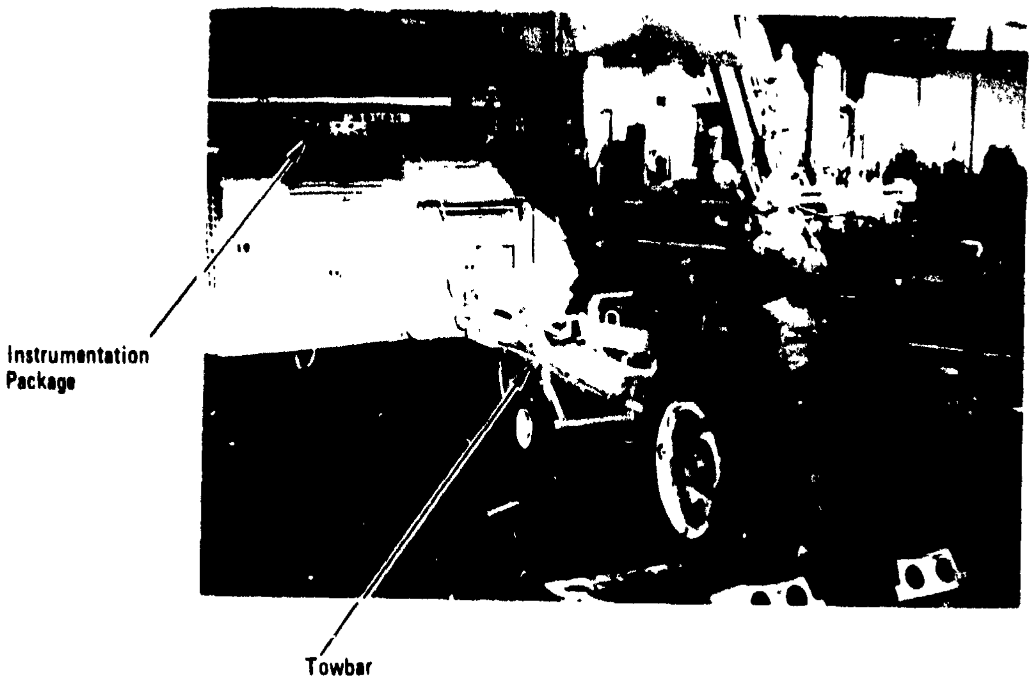

Figure 2-1. Overall View of Towbar and Instrumentation Package

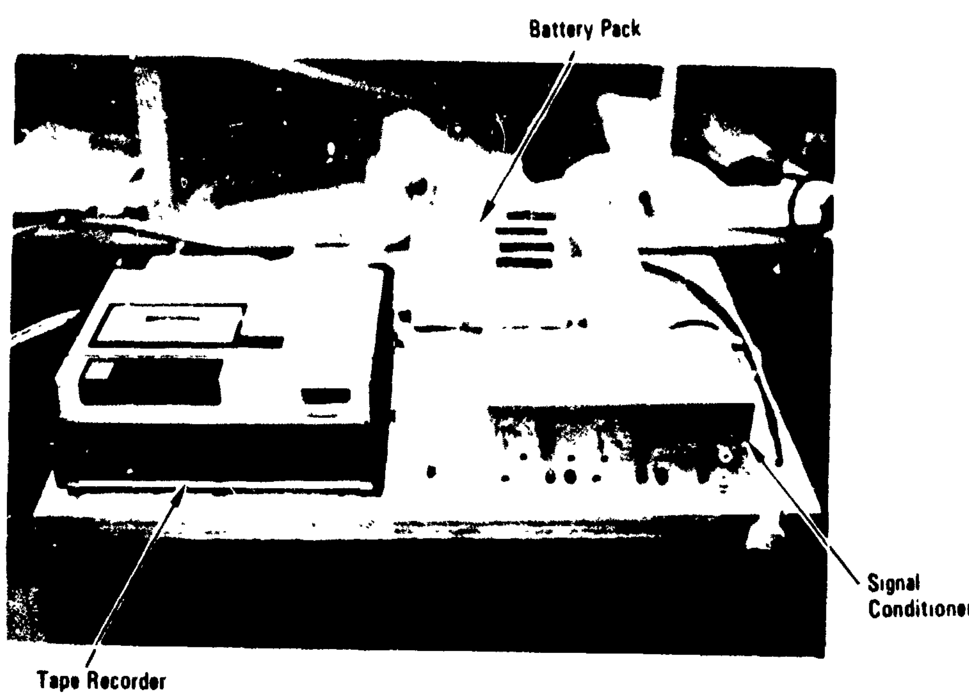

Figure 2-2. Instrumentation Package Layout

provides all necessary electrical power for the system; no external power is required. The equipment shown in Figure 2-2 was used in this form for the LAX tests. For the Dorval cold-weather tests, the equipment was packaged in a metal suitcase for protection.

The nose wheel speed sensor is shown in Figure 2-3. An electrical generator is attached to the towbar, and the wheel on the generator is spring-loaded into contact with the nose tire. The nose gear steering angle transducer is shown in Figure 2-4. This is a linear transducer with a cable that wraps around the steering collar. The transducer is mounted on a plate which attaches to the nose gear with the two wing nuts shown in Figure 2-4. When the tow is complete, the wing nuts are removed, the mounting plate is taken off, and the signal line from the transducer is disconnected. A plug on the tug end of the towbar allows the instrumentation package to be separated from the towbar.

The only difficulty encountered with the instrumentation during the tests was the delicacy of the nose wheel speed generator. This was originally mounted so that the sensor wheel contacted the inside of the nose tire. In this position it was more vulnerable to accidental abuse during towbar hook-up and disconnect. Twice the generator was broken prior to being relocated to the position shown in Figure 2-3. In this position no further damage occurred.

2.2 TOWING TEST RESULTS, LAX

2.2.1 Test Conditions

The LAX tests were conducted during the week of December 4 through 8, 1978. A summary of the LAX towing test conditions is shown in Table 2-1. TWA does the towing for Eastern Airlines (EAL) at LAX, so measurements were made for both TWA and EAL flights. All towing was performed with an International Harvester (Hough) T-500S tug. This is a low profile, twin-engine tug with a gross weight of 110,000 pounds, designed specifically for towing the L-1011. The approximate towing paths are indicated in Figures 2-5 and 2-6. The two long tows to and from the hangar (Runs W-1 and

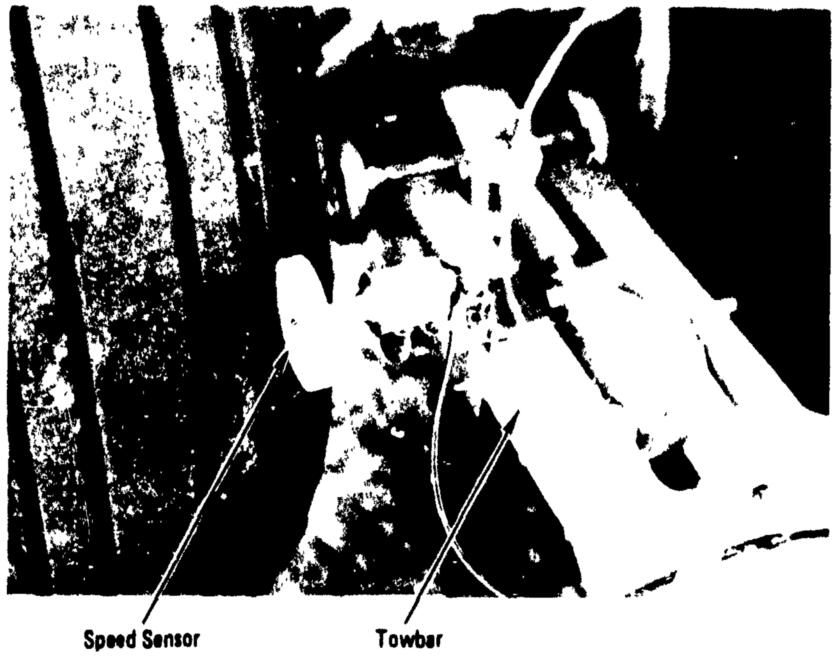

Figure 2-3. Location of Nose Wheel Speed Sensor

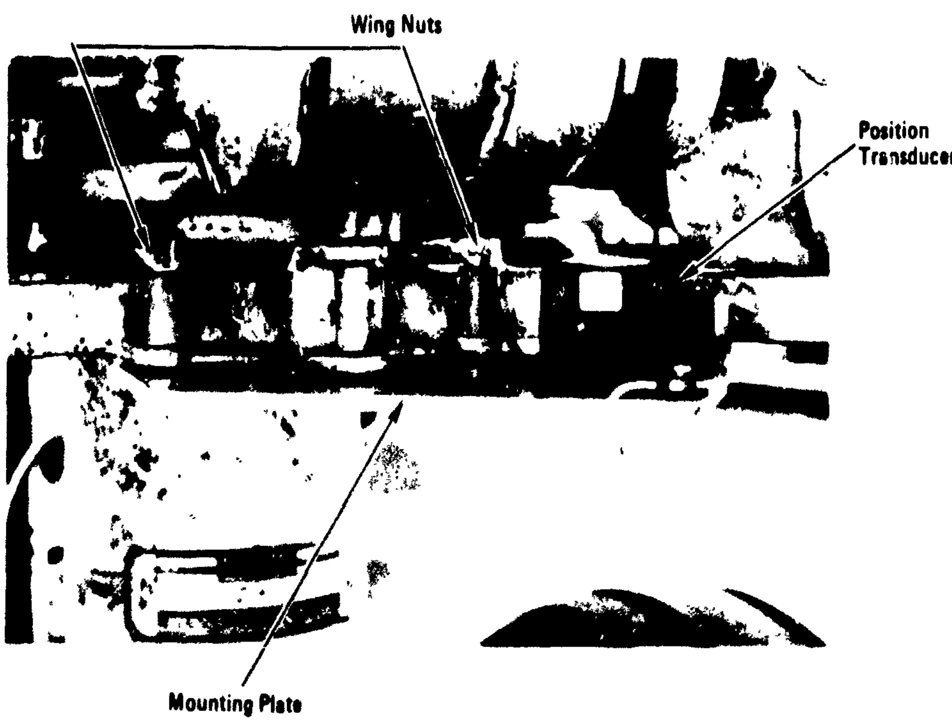

Figure 2-4. Nose Gear Steering Angle Transducer Installation

TABLE 2-1. SUMMARY OF LAX TOWING TEST CONDITIONS

Date	Run	Flight	Gate	Weight, lb	cg	Run Times min:sec
12/4/78	M-1	TWA 38	30	407725	27.7	4:18
	M-2	TWA 66	35	399221	24.9	2:17
	M-3	EAL 81	37B*			2:15
	M-4	EAL 84	37B	360050	24.0	3:07
12/5/78	T-1	TWA 14	30	366130	27.1	4:18
	T-2	TWA 66	35	377409	28.6	2:31
	T-3	EAL 81	37B*	300000		2:23
	T-4	EAL 84	37B	353732	26.5	2:44
12/6/78	W-1	-	Hangar to 37B	"light"		16:16
	W-2	TWA 66	37B	380448	26.6	3:35
12/7/78	Th-1	EAL 82	37B	395000	23.5	3:03
	Th-2	TWA 38	30	370406	25.1	4:39
	Th-3	TWA 66	37B	384592	25.2	4:10
	Th-4	TWA 840	35	373238	25.2	2:01
	Th-5	-	35 to Hangar	"light"		10:28
12/8/78	F-1	FAL 82	37B	380000	25.5	2:40
	F-2	TWA 38	30	410622	26.5	3:10
	F-3	TWA 66	37B	388585	25.3	2:16

*Arrival

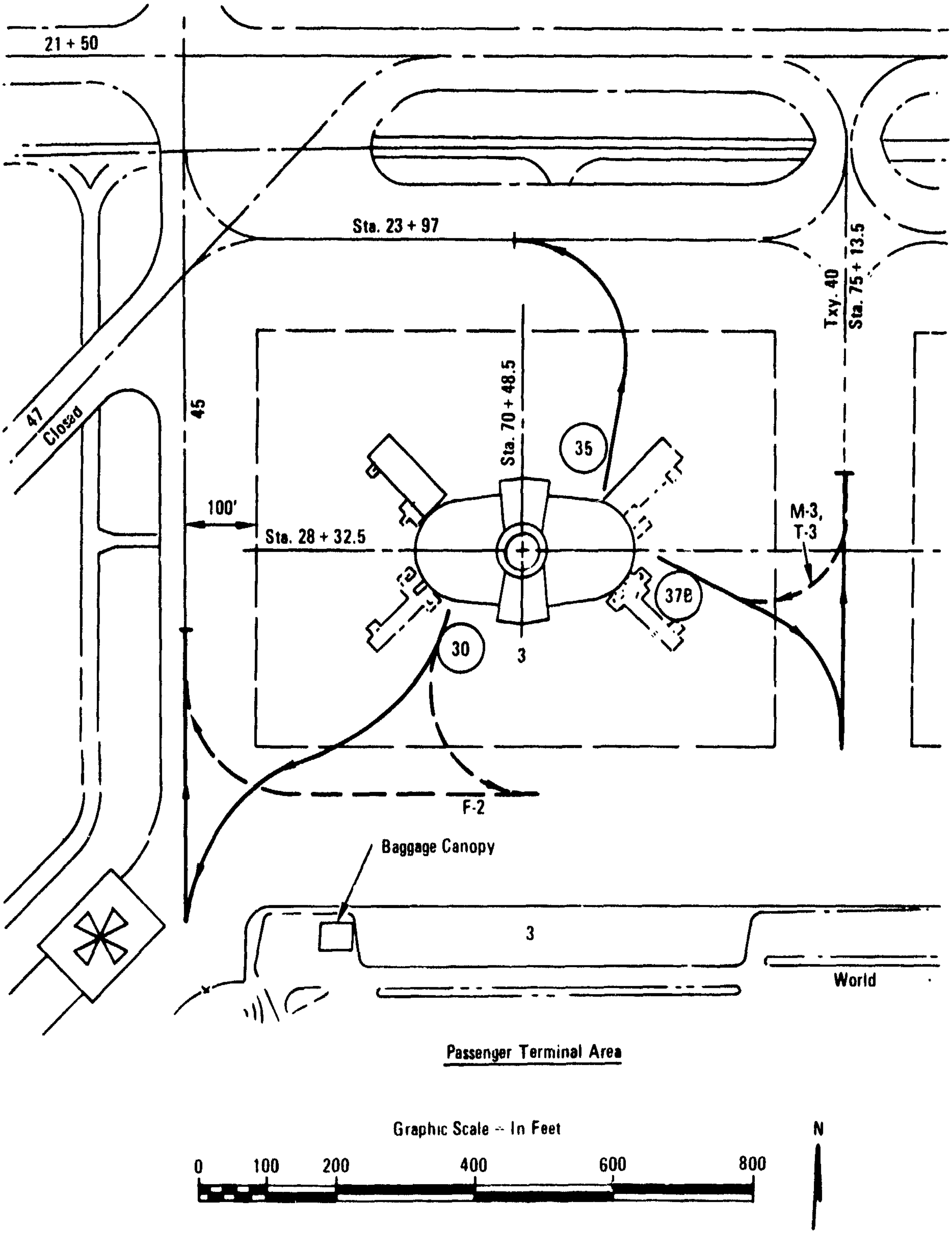

Figure 2-5. Towing Paths at Satellite 3, LAX Towing Tests

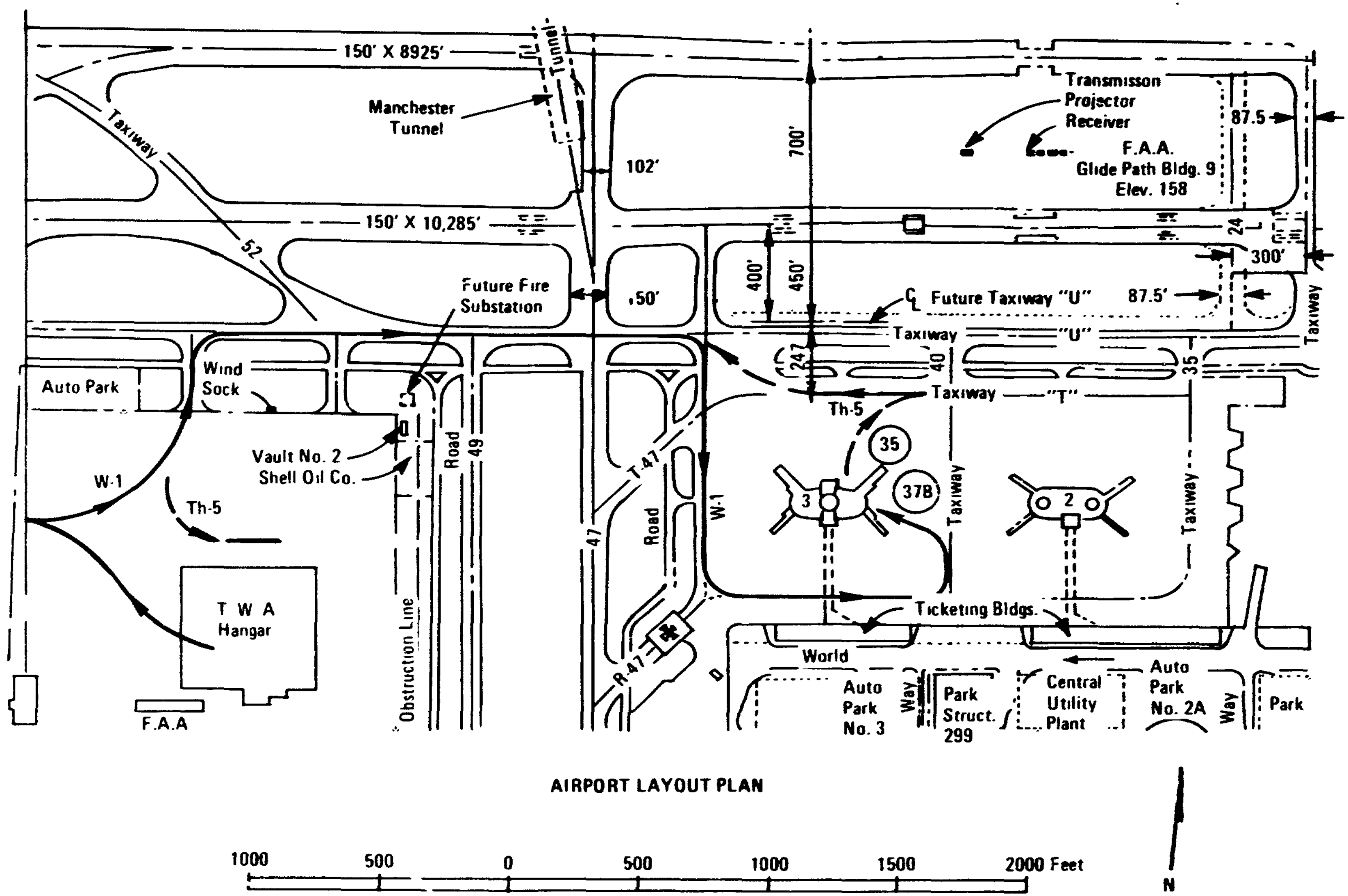

Figure 2-6. Towing Paths To and From TWA Hangar, LAX Towing Tests

Th-5) are shown in Figure 2-6; the solid line is Run W-1. The total length of tow W-1 is about 6400 feet, and the tow required 16 minutes. The Th-5 tow from Gate 35 to the hangar is approximately 4300 feet and required 10.5 minutes. The remaining tows occurred at three gates at Satellite 3. Figure 2-5 illustrates the towing paths identified by gate number. The dashed line path from Gate 30 applies to tow F-2 only; all other operations at Gate 30 followed the solid line path. The path followed depends upon the crew, with both paths normally used about equally. The dashed line for Gate 37B shows the towing path used for arrivals M-3 and T-3. The solid line is used for departures. M-3 and T-3 are the only arrivals during the test program.

For all the towing paths in Figure 2-5, the engines are off during the pushback phase, and generally No. 1 or No. 2 engine start-up is initiated during the pull-forward phase. At Gate 35 there is no pull-forward phase; the towbar is disconnected after the push-back. The total towing time represented by all the tests in Table 2-1 is 1 hour 16.2 minutes, with about 50 minutes representing operational tows at Satellite 3.

2.2.2 Sample Towing Load Histories

Figure 2-7 shows a typical set of response-histories, in this case for Run Th-1. This run is an operational push-out and pull-forward from Gate 37B. Referring to Figure 2-7, the following phenomena can be observed:

- 0-7 sec — Pull airplane forward to release wheel chocks, towbar axial load is tension.
- 7-22 sec — Dynamic compression loading on nose gear during push-out, including one load reversal into tension.
- 22-97 sec — Nearly steady compression (2000-5000 pounds) during push-out. Peak velocity ≈ 3 mph
  Left steering ≈ 45°
- 97-105 sec — Tension peaks on towbar as tow vehicle stops airplane.

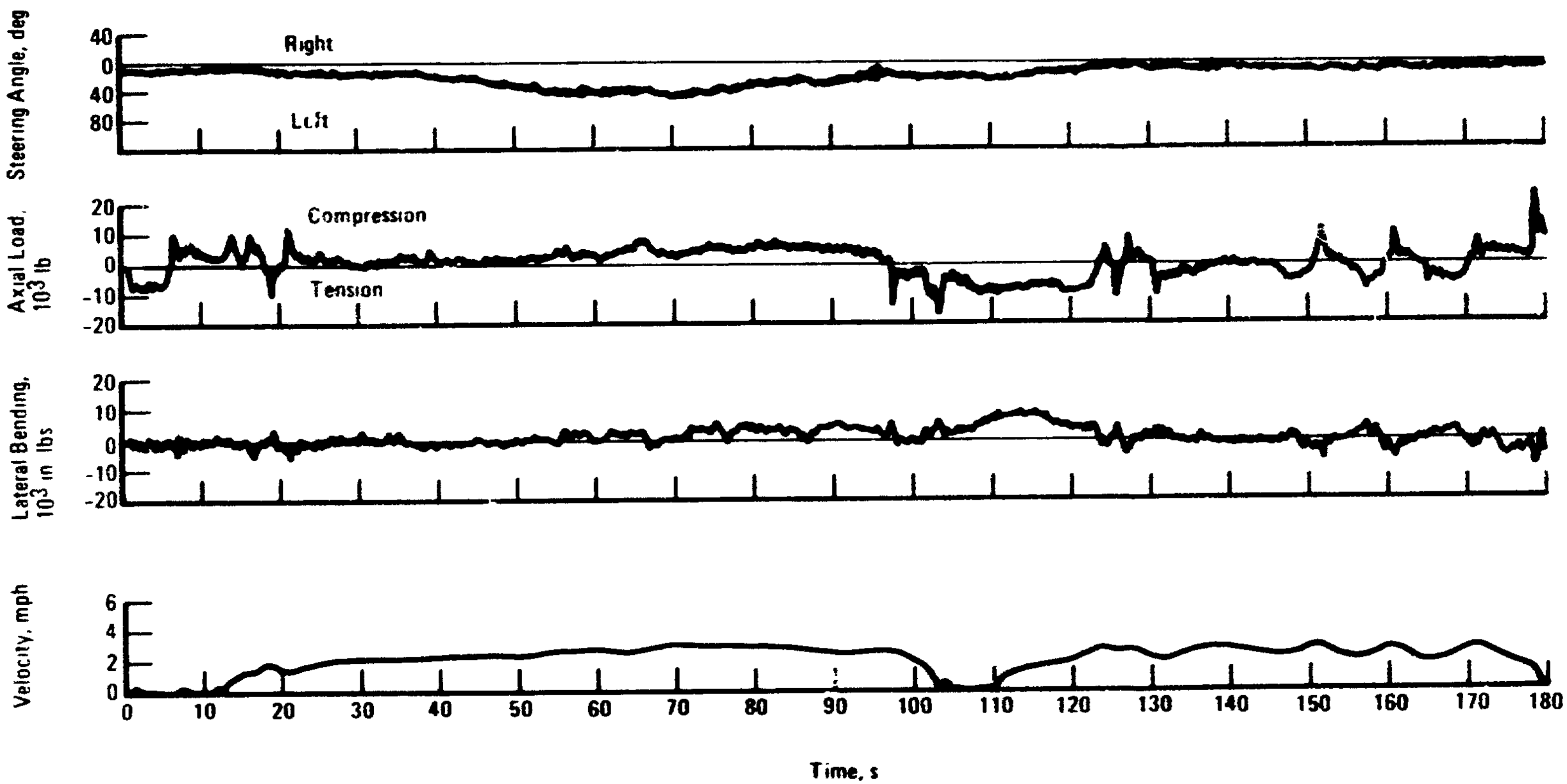

Figure 2-7. Typical Towing Test Results

- 105-177 sec Forward pull with 5 load reversals into compression. Steady pulling load is about zero, No 2 engine running during pull-out. Somewhat irregular tow with velocity fluctuations between 2 and 3 mph.
- 177-180 sec Peak compression loading (24,000 pounds) as tow vehicle stops the airplane.

While the detailed response-histories of each tow are unique, the general features evident in Figure 2-7 are typical. The major towbar loads occur during initial breakout and while stopping and restarting the airplane. Also, there are almost always a number of load reversals during the "steady" towing. The single largest axial load is often at the end of the tow as the airplane is stopped.

The towbar axial load natural frequencies are in the order of 1.5 Hz during high loading (at 7.5 sec and 178 sec, for example), and as low as 0.6 Hz during low loading (30-50 sec). The reason for this large range is that the cushioned-hitch on the tow vehicle has a highly nonlinear spring rate, very soft at low loads and progressively stiffer at high load levels.

2.2.3 Test Results

Table 2-2 is a summary of the peak axial towbar loads and the maximum towing velocities for all the LAX tests. For Runs M-2 through M-4 and T-3 and T-4, the nose wheel speed sensor was inoperative, due to the difficulties described previously. Also shown in Table 2-2 are overall maximum and average values for all the tests. The overall average velocity during pulling (4.2 mph) was 50 percent higher than the corresponding value during pushing. The highest tow velocity achieved was 9.0 mph during the long tow from the hangar to the terminal with an empty airplane.

Conversations with the tow vehicle operators indicate that the pulling velocities during the Monday through Thursday tests may be somewhat less than typical, and that the Friday tests may be more representative. Using the Friday data only, the average velocities were 2.87 pushing and 6.33 pulling. However, visual observation of other towing operations at LAX tend to

TABLE 2-2. SUMMARY OF LAX TOWING TEST RESULTS

Run No.	Peak Axial Loads, 10^3 lb		Maximum Towing Velocity, mph	
	Compression	Tension	Pushing	Pulling
M-1	13	22.8	2.8	2.8
M-2	14	9	-	-
M-3	24	28	-	-
M-4	20.6	14.3	-	-
T-1	14	13.5	2.7	3.6
T-2	17	6.5	2.5	-
T-3	16.5	14	-	-
T-4	17	13	-	-
W-1	22.5	18.3	3.5	9.0 ①
W-2	16	10.8	2.2	2.6
Th-1	24	18.7	3.0	2.8
Th-2	14.1	13	3.0	3.8
Th-3	10.2	10.8	2.7	3.1
Th-4	13	-	2.6	-
Th-5	25	18.8	2.6	8.4 ①
F-1	20	14	2.8	4.2
F-2	18	27.4	3.1	8.1
F-3	28.8	26	2.7	6.7
Overall Maximum	28.8	28.0	3.5	9.0 ③ 8.1 ②
Overall Average	18.2	16.4	2.78	5.0 ③ 4.2 ②

① Long tows on main taxiway, empty airplane

② Excluding two long tows with empty airplane

③ Including two long tows with empty airplane indicate that the F-2 and F-3 tows were unusually fast, and also unusually rough. Therefore, the F-2 and F-3 tows should probably be considered somewhat non-typical, although an accurate estimate of the frequency of occurrence of these speeds and loads would require a much more extensive data base.

To put the loads in Table 2-2 into perspective, the following load levels for the L-1011-1 are given:

- Limit design towing load = 70,200 lb (at W = 468,000 lb, steering angle $\leq \pm 20^{\circ}$)
- Maximum towing load in nose gear fatigue spectrum = 31,160 lb

The maximum load encountered during the LAX testing was 41 percent of limit design load, and 92 percent of the largest towing load in the fatigue spectrum.

2.3 TOWING TEST RESULTS, DORVAL

2.3.1 Test Conditions

The cold-weather towing tests were performed at Dorval Airport, Montreal, Quebec, during the week of February 26 through March 2, 1979. The ambient temperature during the week ranged from about 16°F to 40°F. Surface conditions varied from dry pavement to 3-4 inches of compact snow and ice, depending upon location and time. In general, the loading ramps and main taxiways are kept free of snow as much as is practical, but the taxiways to the maintenance hangar and the ramp areas around the hangar are normally covered with compact snow.

Figure 2-8 shows the test instrumentation setup for a typical tow at Dorval. The instrumentation package is contained within the metal suitcase partially visible at the extreme left of Figure 2-8. The nose gear torque arms are shown disconnected in Figure 2-8. This is standard policy for Air Canada in all towing operations. This procedure renders the steering angle transducer inoperative, so that steering angle information is not available for any of the Dorval tows. Figure 2-9 illustrates typical compact snow surface conditions. This is a photograph taken at the conclusion of a straight pushback from the terminal.

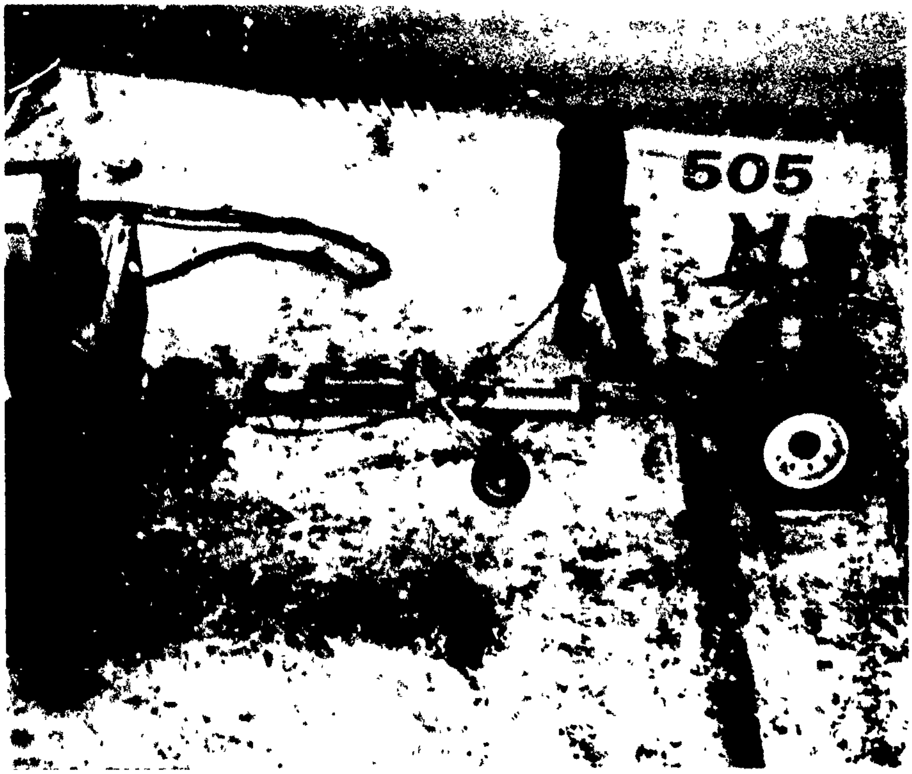

Figure 2-8. Towing Test Instrumentation, Dorval Tests

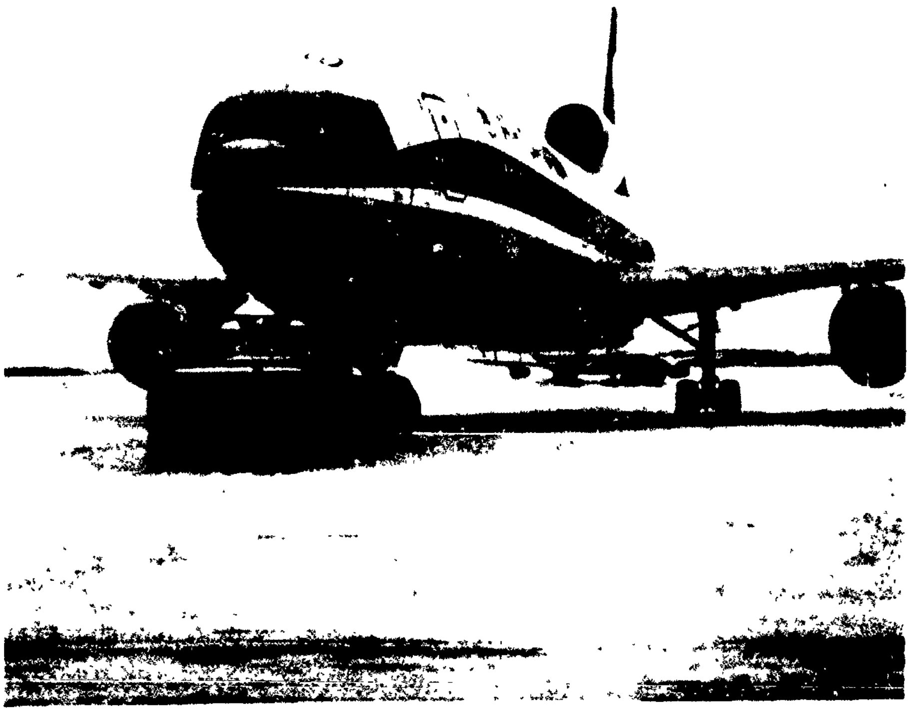

Figure 2-9. Typical Surface Conditions, Dorval Tests

Table 2-3 is a summary of the towing test conditions performed at Dorval, with the cooperation of Air Canada. Runs T-2, W-1, Th-3, and F-1 are tows between the terminal and the maintenance hangar. These tows vary in length from around 6200 feet to 8700 feet. The remaining runs are all straight pushbacks on the order of 200-400 feet. All tow vehicles use chains on all four wheels at all times. At Dorval, terminal area pushbacks are done with a T-300S tug, which is a relatively small (40,000 pound), single-engine vehicle with a maximum drawbar pull of around 30,000 pounds. The small tug is used due to the limited distance between the L-1011 nose gear in the parked position and the terminal building. The larger T-500S tug, which was used exclusively at LAX, was used for all the long tows between the terminal and the hangar. In addition, this tug was used during Run T-1, with the tug behind the nose gear pulling the airplane backwards.

2.3.2 Test Results

Table 2-4 is a summary of the peak towbar loads and towing velocities for each condition. The only forward tows occur during the long maintenance tows; the average velocity for these tows is about the same as at LAX. The average velocity for the pushback tows is also very close to the LAX results (3.09 vs. 2.78 mph). For Run T-1, the tug is underneath the airplane behind the nose gear. For this case, "tension" refers to a forward load on the nose gear, with the towbar actually in compression. Therefore, all "tension" loads in Table 2-4 are actually forward acting on the nose gear. The only significant tension loads occur during the long maintenance tows. The overall peak tension load is comparable to that at LAX (26,050 vs. 28,000), with each peak load occurring when the tug shifts from second to third gears.

Observations of airplane towing on intermittent dry/icy surfaces indicate that the tug with chains appears to be unaffected by transitions from compact snow/ice to dry surfaces. Riding as a passenger in a tug under these conditions also indicates no discernible change in traction during a transition between wet and dry surfaces. Conversations with tow vehicle drivers yield the information that the maximum towing loads occur when the airplane is pushed or pulled across a ridge of snow on the order of 6-12 inches high,

TABLE 2-3. SUMMARY OF DORVAL TOWING TEST CONDITIONS

Date	Run No.	Flight	Gate	Weight, Pounds	Run Time Min:Sec.
2/27/79	T-1	791	21	-	3:24
	T-2	-	4 to Hangar	empty *	18:33
2/28/79	W-1	-	Hangar to 21	empty *	19:25
	W-2	791	21	286,400	1:35
	W-3	105	4	330,000	2:37
3/1/79	Th-1	791	21	313,800	1:41
	Th-2	105	4	312,990	1:44
	Th-3	-	4 to Hangar	empty *	13:14
3/2/79	F-1	-	Hangar to 4	empty *	21:17
	F-2	791	21	297,020	1:23
	F-3	105	4	362,600	2:46

*Empty weight denotes no passengers and an unknown light fuel loading, resulting in a weight of approximately 250,000 pounds.

with occasional tows through portions of snow as high as 18 inches. These ridges only occur during the plowing operation immediately after a fresh snow, before the snow plowing/blowing/removal operation is complete. This condition was not encountered during the Dorval testing, even though fresh snowstorms occurred twice.

2.4 TOWING TEST RESULTS, PALMDALE

2.4.1 Test Conditions

The purpose of the Palmdale towing tests is to determine towing loads under a variety of controlled conditions. For the majority of these runs, a towing path was followed at Palmdale which closely approximates a typical towing path for an Eastern Airline L-1011 in the Southwest Terminal region at Boston-Logan. Figure 2-10 is a partial map of the Southwest Terminal region

TABLE 2-4. SUMMARY OF DORVAL TOWING TEST RESULTS

Run No.	Peak Towbar Axial Loads, lb		Maximum Towing Velocity, mph	
	Compression	Tension	Pushing	Pulling
T-1	18,240	2,740	-	-
T-2	6,480	14,260	2.5	6.9
W-1	8,900	26,050	3.4	9.3
W-2	14,010	790	3.0	-
W-3	10,260	5,480	3.3	-
Th-1	16,990	3,040	3.1	-
Th-2	10,970	0	3.1	-
Th-3	14,900	20,190	2.3	8.6
F-1	11,480	14,840	2.9	8.2
F-2	13,060	710	4.0	-
F-3	16,470	6,170	3.3	-
Overall Maximum	18.240	26,050	4.0	9.3
Overall Average	12,890	8,570	3.09	8.25

at Boston-Logan, showing typical departure and arrival towing paths with enforced towing to the limit line defined by the proposed Massport regulations. In Figure 2-11 is shown the approximation to these paths used for the Palmdale tests. Both the departure and arrival towing paths originate at Stall 11, and terminate down the flight line at Stall 8 or 9. Following each test, the airplane is pushed back into Stall 11 for the next test. Data are recorded for these pushbacks, but are only used as supplemental information. The actual towing paths used are straightened out somewhat to avoid obstructions on the flight line. Also, the departure path used at Palmdale is a mirror image of the path employed at Boston-Logan. This is necessary to fit the pattern into the available space.

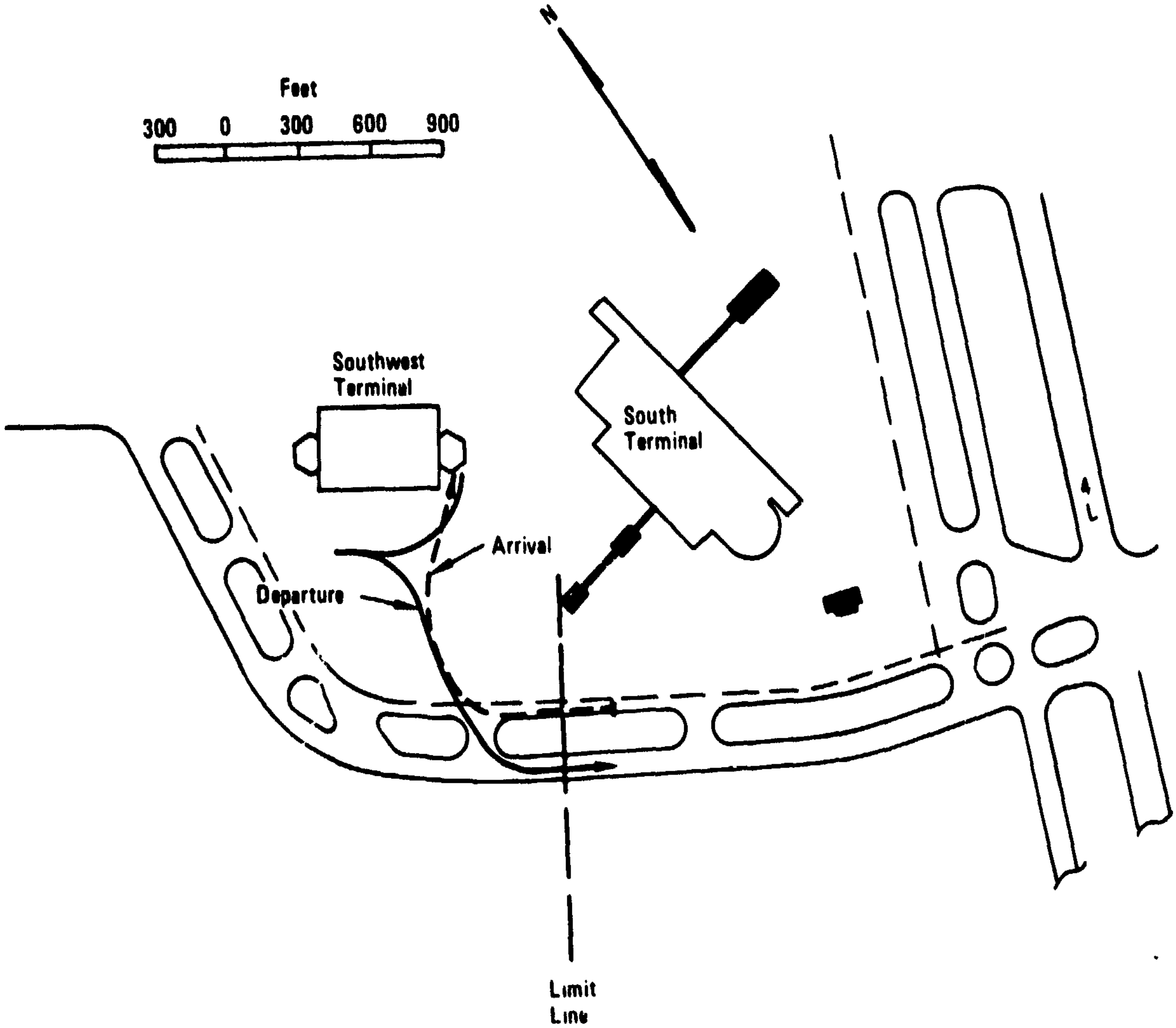

Figure 2-10. Southwest Terminal Region at Bostor-Logan

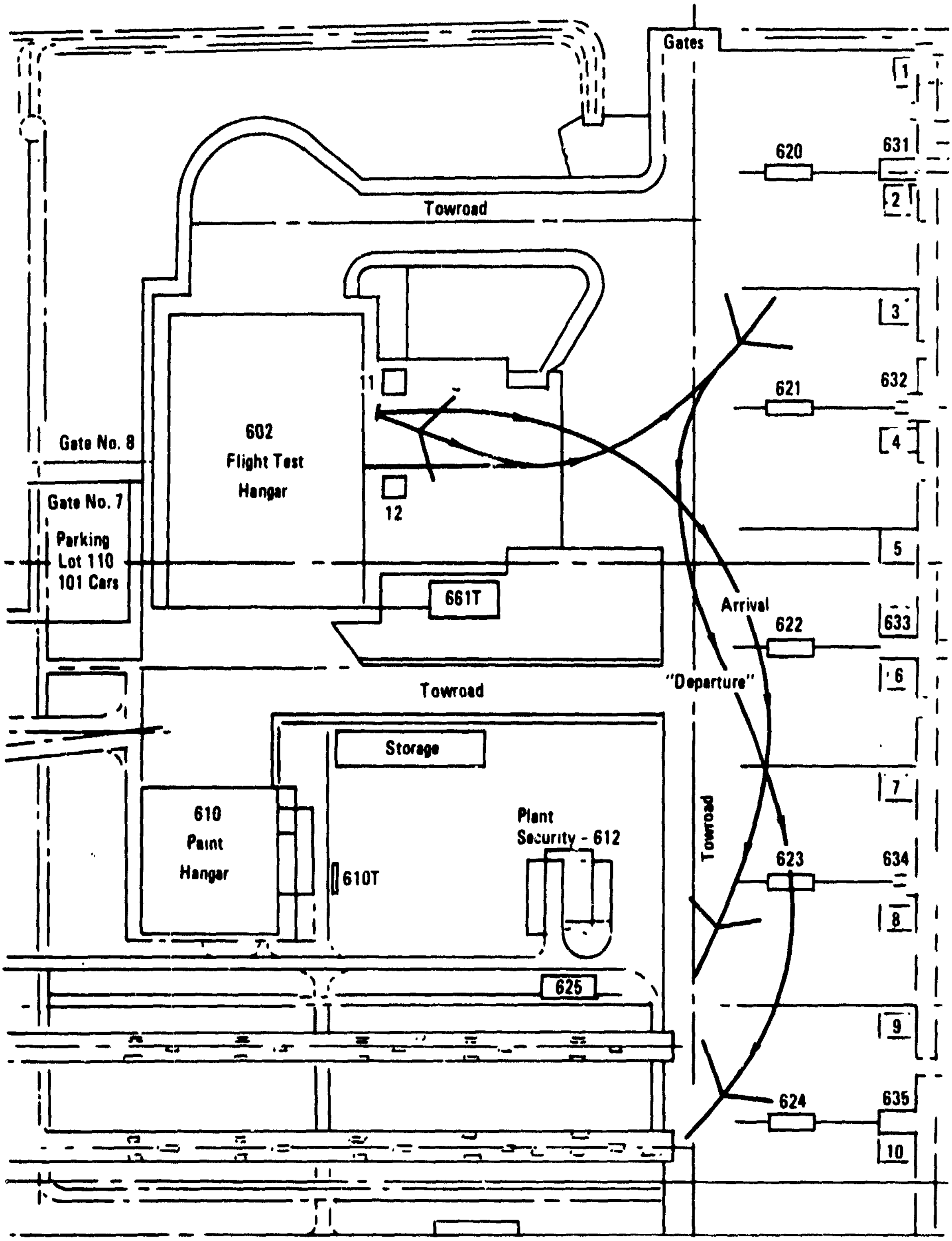

Figure 2-11. Palmdale Towing Test Routes

Table 2-5 shows the originally planned Palmdale test program. Runs 1-18 represent variations in airplane weight, center-of-gravity (cg) position, tire pressure and towing velocity, including both arrival and departure paths as defined in Figure 2-11. Tests 19 and 20 are straight line tows over the area of maximum slope available for tests. Tests 21 and 22 are constant steering angle circular path tows involving a push-back, stop, and pull-forward to near original position, with a change in airplane heading of at least 90° at the end of the pushback.

Tests 23 through 26 are special conditions. Test 23 is intended to maximize the draw-bar pull required to maintain a steady speed. Test 24 represents straight, level towing at the fastest speed attainable consistent with the tug operator feeling secure in his control of the airplane. Test 25 is an unusually rough or abrupt start and stop within the constraints of safe operation. Test 26 is a tow across a drainage ditch or similar abrupt slope change.

During the actual testing, it was discovered that certain conditions required an inordinate amount of time to set up. In particular, it was very time consuming to achieve variations in airplane cg position and tire pressures. Table 2-6 shows the test conditions actually run. The tests deleted include

- 8, 10
- 11, 12, 14
- 23

Runs 8 and 10 are forward and aft cg at light weight; cg variations were run at a heavy weight which is of more interest. Runs 11, 12 and 14 are tire pressure variations; one run at a tire pressure of 150 psi (compared to 200 psi nominal) was deemed sufficient to define the sensitivity of towing loads to this parameter. Run 23 is a high drag condition consisting of maximum takeoff gross weight, full aft cg and low tire pressure. This condition is very difficult to set up, and represents a combination of extremes that would never be encountered in actual service. The actual testing was accomplished on three separate dates, as indicated in Table 2-6. A T-800S tug, designed for the B-747, was used for all tows except Run 24, which was performed with

TABLE 2-5. PROPOSED PALMDALE L-1011 TOWING TEST PROGRAM

Test No.	Airplane Weight, 10^3 lb	CG Pos.	Tire Press.	Velocity mph	Taxiing Slope	Towing Path	Comments
1	380	25	Nominal	3-5	Level	Dep.	Basic nominal departure
2	300	25	Nominal	3-5	Level	Arr.	Basic nominal arrival
3	420	25	Nominal	3-5	Level	Dep.	Heavy weight departure
4	340	25	Nominal	3-5	Level	Arr.	Heavy weight arrival
5	340	25	Nominal	3-5	Level	Dep.	Light weight departure
6	260	25	Nominal	3-5	Level	Arr.	Light weight arrival
7	380	20	Nominal	3-5	Level	Dep.	Forward cg departure
8	300	16	Nominal	3-5	Level	Arr.	Forward cg arrival
9	380	32	Nominal	3-5	Level	Dep.	Aft cg departure
10	300	32	Nominal	3-5	Level	Arr.	Aft cg arrival
11	380	25	High	3-5	Level	Dep.	High tire pressure departure
12	300	25	High	3-5	Level	Arr.	High tire pressure arrival
13	380	25	Low	3-5	Level	Dep.	Low tire pressure departure
14	300	25	Low	3-5	Level	Arr.	Low tire pressure arrival
15	380	25	Nominal	≥ 8	Level	Dep.	High velocity departure
16	300	25	Nominal	≥ 8	Level	Arr.	High velocity arrival
17	380	25	Nominal	≤ 3	Level	Dep.	Low velocity departure
18	300	25	Nominal	≤ 3	Level	Arr.	Low velocity arrival

TABLE 2-5. PROPOSED PALMDALE L-1011 TOWING TEST PROGRAM (Continued)

Test No.	Airplane Weight, 10^3 lb	CG Pos.	Tire Press.	Velocity mph	Taxiing Slope	Towing Path	Comments
19	380	25	Nominal	>3	Uphill	Straight	Uphill straight tow on maximum available slope
20	380	25	Nominal	>3	Downhill	Straight	Downhill straight tow on maximum available slope
21	380	25	Nominal	<5	Level	Circle	Constant 25° steering angle, push back, pull fwd.
22	380	25	Nominal	<5	Level	Circle	Constant 50° steering angle, push back, pull fwd.
23	420	32	Low	>3	Uphill	Straight	Maximum drag condition
24	380	25	Nominal	>10	Level	Straight	High velocity straight tow
25	380	25	Nominal	>5	Level	Straight	Abrupt start and stop
26	380	25	Nominal	3-5	Level	Straight	Tow across drainage ditch

TABLE 2-6. ACTUAL PALMDALE L-1011 TOWING TEST CONDITIONS

Test No.	Date Run	Airplane Weight, 10^3 lb	CG Position, % MAC	Tire Pressure psi
1	1/29/79	380	26.3	200
2	2/12/79	300	25.9	200
3	4/5/79	416.0	27.1	200
4	1/29/79	340	26.5	200
5	1/29/79	340	26.5	200
6	1/29/79	270	24.6	175
7	4/5/79	380.4	19.8	200
9	4/5/79	378.2	33.7	200
13	4/5/79	378.2	33.7	160
15	1/29/79	380	26.3	200
16	2/12/79	300	25.9	200
17	1/29/79	380	26.3	200
18	1/29/79	300	25.9	200
19	1/29/79	380	26.3	200
20	1/29/79	380	26.3	200
21	1/29/79	380	26.3	200
22	4/5/79	376.4	26.1	200
24	4/5/79	376.4	26.1	200
25	1/29/79	380	26.3	200
26	1/29/79	380	26.3	200

a T-180 FM, a small single-engine tug. (The T-800S burned out an engine just prior to Run 24.)

The instrumentation for the Palmdale tests included measurement of the four basic towing response parameters. However, the data were fed into the flight test PCM data recording system rather than using the 4-track cassette recorder. Additional airplane response parameters recorded include

- Cockpit vertical acceleration
- Center of gravity vertical and longitudinal acceleration
- Nose gear strut extension
- Nose gear side load

2.4.2 Test Results

The Palmdale test results are summarized in Table 2-7. For Runs 1-18, the loads were lower than those measured at LAX and Dorval, with the exception of Run 16. During this run, the single largest peak towbar load was obtained (36,200 pounds tension). This load occurred when the tug shifted gears at around 4 mph. The tug was being driven by an inexperienced operator. In general, the results of the parameter variations in Runs 1-18 were inconclusive. Runs 3 through 6 indictted an increase in peak loads with increased airplane weight, but the absolute levels were very low and the trend was not entirely consistent. Runs 7 and 9 indicated no significant variation in towbar loads with cg position, and Run 13 indicated that low tire pressure (160 psi vs. 200 nominal) does not lead to unusually high loads. The high and low speed tows (Runs 15-18) yielded typical results, with the single exception of the large peak during Run 16.

The results of Run 16 and also Run 25, wherein the tug drivers deliberately tried to achieve high loads, indicated that driver technique is by far the dominant parameter determining towbar loads. Even airplane weight must be considered a parameter of secondary influence, since the peak load during Run 16 occurs with an airplane weight of only 300,000 pounds. Also, Run 16 was rerun following the occurrence of the large tension load, and during the rerun the peak tension load was only 13,000 pounds. Therefore, the fact that Run 16 is a high velocity condition does not account for the large load (the rerun achieved an even higher velocity of 6.8 mph). It would be expected that if the test conditions, including tug driver throttle input were very precisely controlled, then the effects of airplane weight and tire pressure would be evident. The required degree of control of driver inputs was not achieved during the Palmdale tests, so that the result are basically a

TABLE 2-7. SUMMARY OF PALMDALE TOWING TEST RESULTS

Test No.	Peak Axial Loads, 10^3 lb		Maximum Towing Velocity, mph	
	Compression	Tension	Pushing	Pulling
1	13.0	8.0	5.0	3.6
2	4.2	12.0	-	3.8
3	12.5	14.1	3.8	3.8
4	8.8	5.5	-	4.2
5	10.6	8.4	5.1	3.9
6	4	8.1	-	3.6
7	12	11.5	5.0	4.1
9	5	11.5	5.5	3.9
13	6.5	12.8	4.8	3.8
15	15.0	9.0	4.0	[1]
16	12.5	36.2	-	5.8
17	12.5	7.0	1.0	2.0
18	10	11.5	-	4.1
19	1	12.0	-	6.5
20	17	2	-	4.4
21	13	9.8	2.5	3.0
22	7.5	16.5	2.2	2.6
24	6	17	-	12.0
25	33.5	33.8	-	-
26	2.0	4.0	-	4.0
Overall Maximum	33.5	36.2	5.5	12.0
Overall Average	10.3	12.5	3.9	4.4
Average Runs 1-18	9.7	12.0	4.3	3.9

[1] No data

statistical sampling of the effects of driver technique. All tows were done with the same driver except those performed on February 12, 1979 (Runs 2 and 16), which were done by the relatively inexperienced driver.

SECTION 3

TOWING LOADS ANALYSIS PROGRAM

3.1 COMPUTER PROGRAM DESCRIPTION

Figure 3-1 illustrates the towing loads analytical model. The airplane is modeled as a rigid body with three degrees-of-freedom; pitch, plunge and fore-aft motion. In addition, the unsprung mass of the nose gear has fore-aft and vertical degrees-of-freedom, and the main gear unsprung mass has a vertical degree-of-freedom. Airplane or tug lateral, roll and yaw motions are not modeled. Therefore, towing turns cannot be analyzed with this program. Each landing gear is modeled as a conventional air-oil oleo with nonlinear load-deflection curve and hydraulic damping. The nose and main gear tires are modeled as linear spring-dampers. The fore-aft structural flexibility of the nose gear is also modeled as a linear spring-damper, with the gear stiffness varying with strut extension.

The tow vehicle also has three degrees-of-freedom. Linear spring-dampers are used for the tires (there is no suspension). A rigid towbar with backlash connects the tug and airplane. The T-500S tow vehicle, used by TWA at LAX for towing the L-1011, has a shock-absorber between the towbar hitch and the tug. This device, termed a cushioned-hitch, yields the nonlinear load-deflection characteristic shown in Figure 3-2. This behavior is achieved by the compression of 2 parallel stacks of 4 rubber springs of 6 inch diameter. The load-deflection characteristic of Figure 3-2 is operable both in compression and tension. The T-800S tug used at Palmdale differs from the T-500S in that the towbar connection to the tug is rigid. For this tug, the towbar is modeled as a linear spring-damper.

The tow vehicle thrust versus forward velocity characteristics (commonly available in brochures) are input to the computer program. Figure 3-3

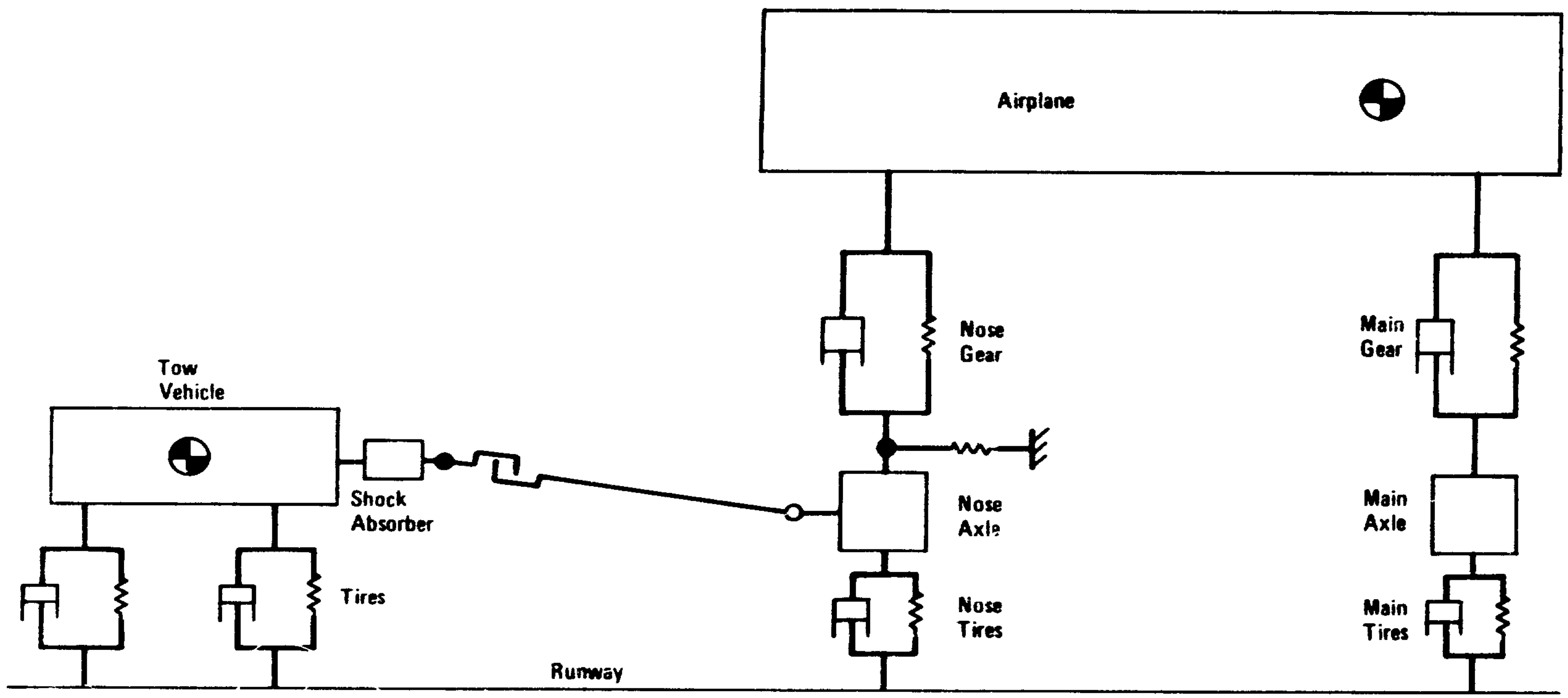

Figure 3-1. Towing Loads Analytical Model

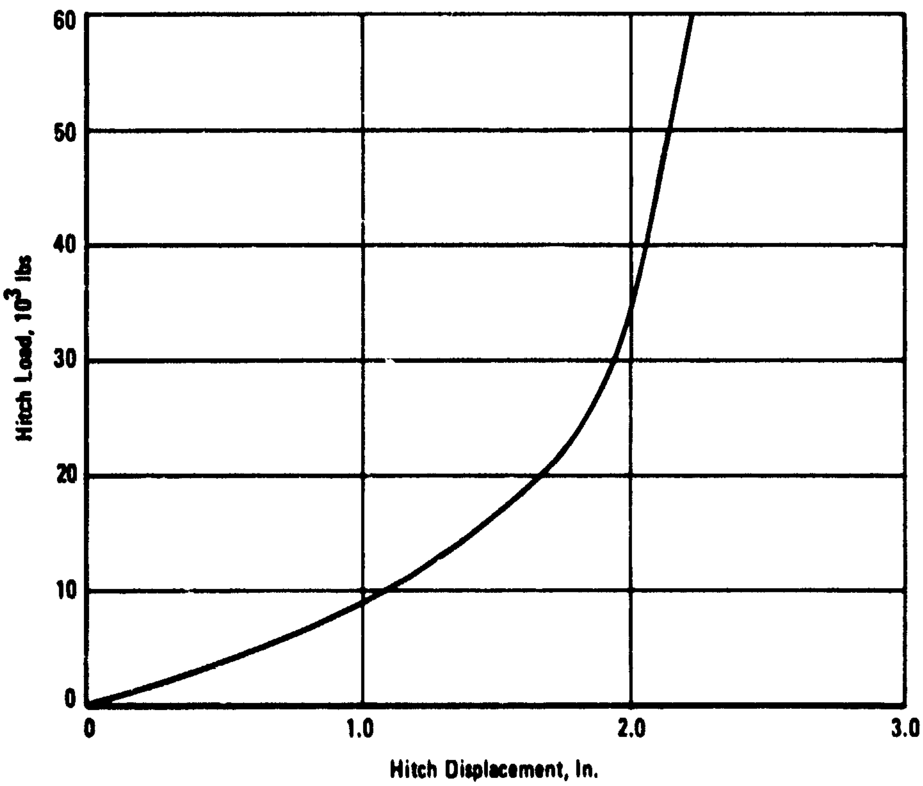

Figure 3-2. Cushioned-Hitch Load-Deflection Curve

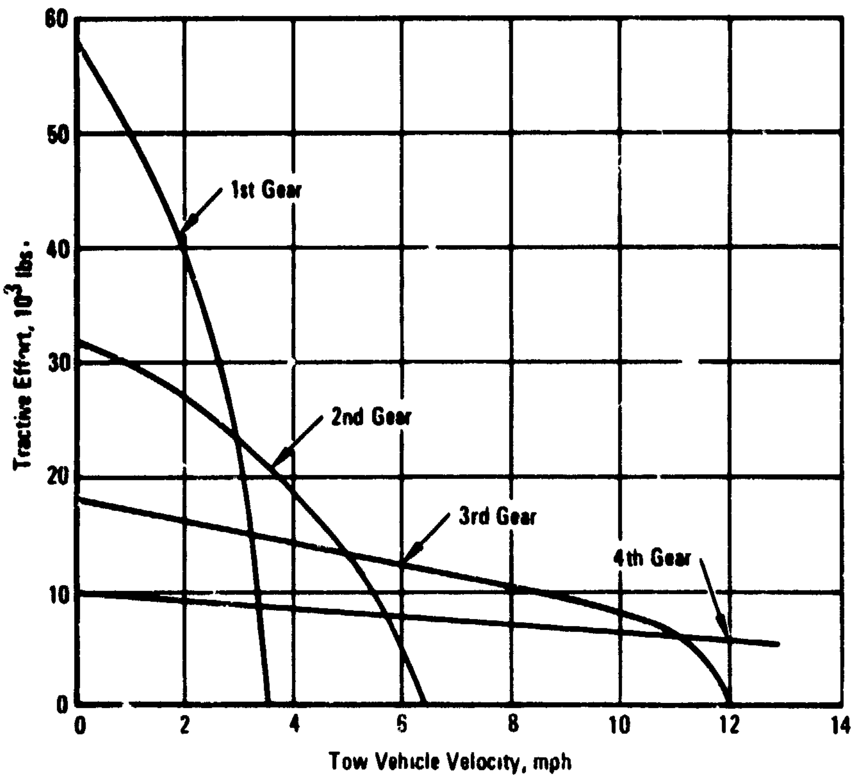

Figure 3-3. Tow Vehicle Performance Characteristics, T-500S

shows the thrust curve (full-throttle) for the T-500S tug. The actual vehicle thrust is calculated as the full-throttle value times a time-varying factor representing normalized throttle position. The analytical model also includes rolling friction of the airplane and tug and allows for tug and airplane braking.

The analytical model dynamic equations are solved using a Continuous System Modeling Program (CSMP). This system is operated with a CRT display screen and contains a flexible plot viewing capability. Direct solutions at the computer terminal with operator interaction allows for rapid determination of analytical results. A listing of the CSMP program is given in Appendix A.

3.2 COMPUTER PROGRAM RESULTS

As a baseline case for the analytical studies, the L-1011-1 at 382,000 pounds is modeled, with a cg position of 25.8 percent MAC, based on average values from the LAX tests. A T-500S tug at a weight of 110,000 pounds is also used. The normalized tug throttle position is ramped in linearly from time zero to the peak value, and then held constant for the remainder of the run.

Figure 3-4 shows the towbar axial load response for a nominal condition in which a maximum normalized throttle position of 0.6 is attained with a rise time of 1.0 seconds. The frequency of oscillation is 1.35 Hz, which is the frequency of the airplane/tug fore-aft response mode. Figure 3-5 shows the forward velocity of both the airplane and the tow vehicle. The lag of the airplane's velocity is due to the backlash in the towbar/hitch connection, and the oscillations of the tow vehicle velocity show the influence of the oscillating towbar load. Eventually the oscillations settle down and the two velocities are equal. Figure 3-6 shows the nose gear strut position, indicating a strut extension of about 1.5 inches compared to the initial static position, due to pitching of the airplane.

Figure 3-7 shows the variation of peak towbar axial load with change in maximum normalized throttle position. Results are shown for both first and second gear starts. Conversations with tug drivers indicate that second

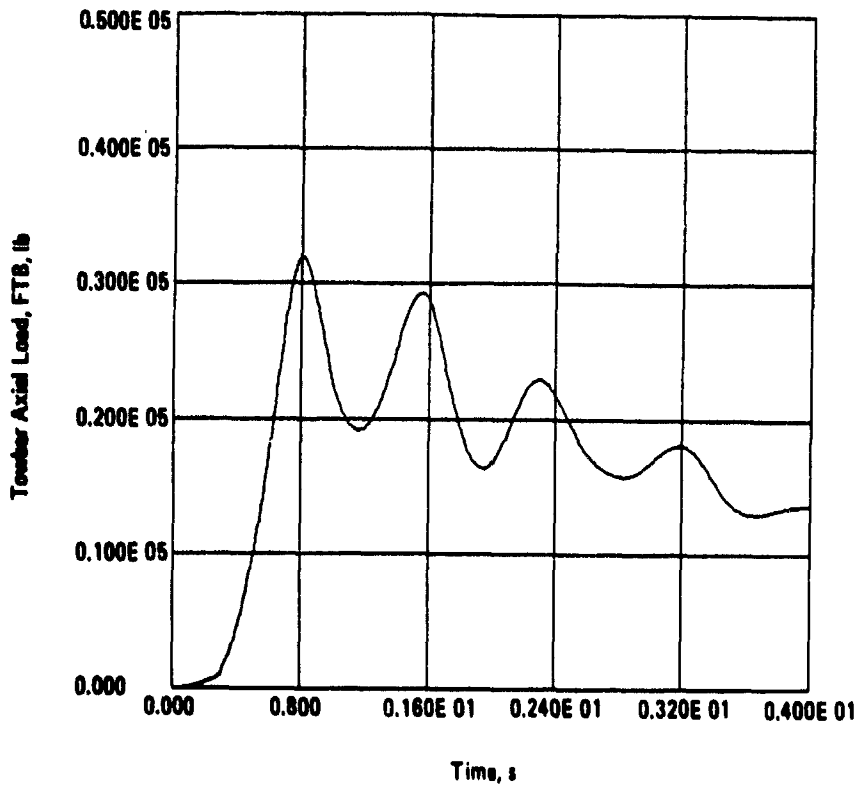

Figure 3-4. Analytical Towbar Axial Load

gear is more commonly used than first. The results given in Figure 3-7 are for a rise time of zero, representing the most abrupt start possible. Also, first gear results are shown for a reverse tow, or pushback. Note that the pushback is slightly more severe than the forward pull, probably due to the stiffer nose gear (fore-aft) when the nose strut compresses due to airplane pitch motion. Figure 3-7 indicates the extreme loading that is theoretically possible with a zero rise time, with peak towbar loads above 80,000 pounds.

Figure 3-8 shows the variation of towbar load with rise time, for a fixed normalized throttle position of 0.6. These curves show the expected reduction of peak load with increasing rise time, until an essentially static response is achieved. With the automatic transmissions used in the tow vehicles, it is clear that very short rise times are not physically possible, and that perhaps one to two seconds is the quickest rise time attaintable. The maximum towbar load for a throttle position of 1.0 and a rise time of 1 second is 47,120 pounds. This reduces to 38,130 pounds for a 2-second rise

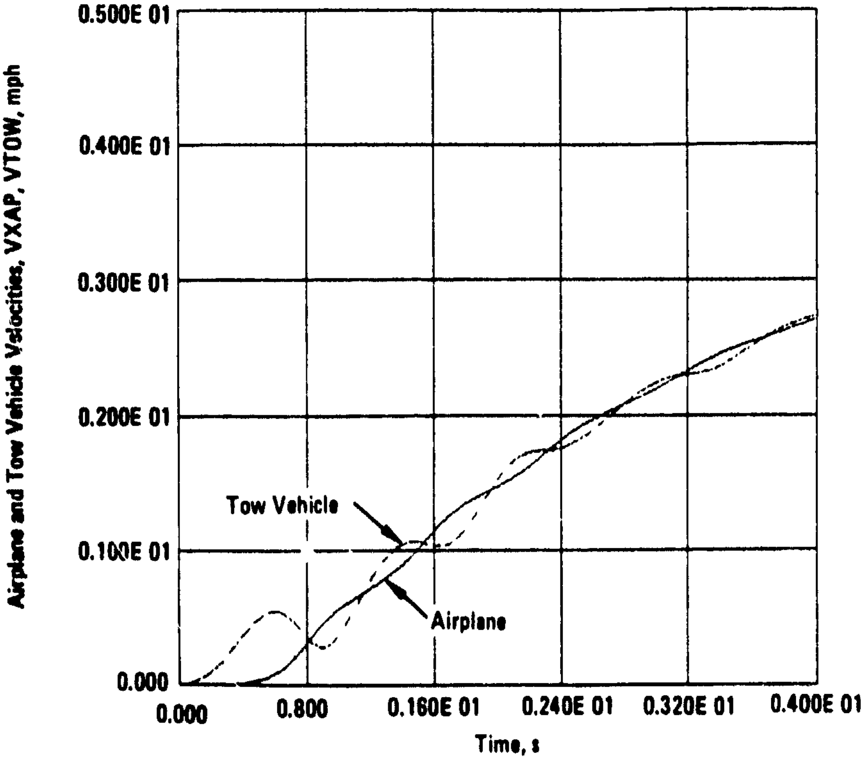

Figure 3-5. Airplane and Tow Vehicle Velocities

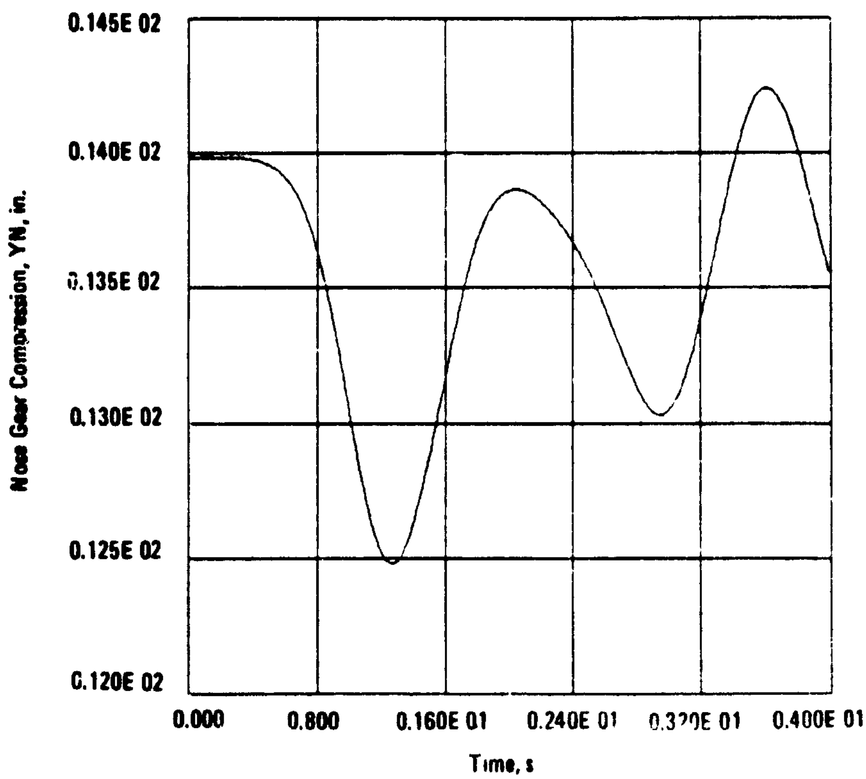

Figure 3-6. Nose Gear Compression

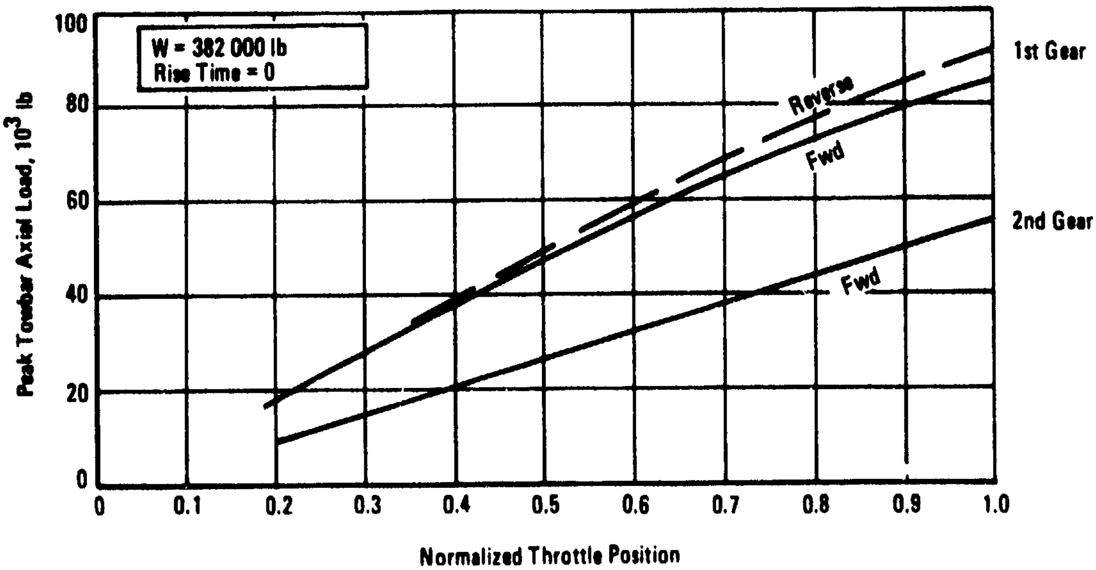

Figure 3-7. Variation of Towbar Load with Normalized Throttle Position

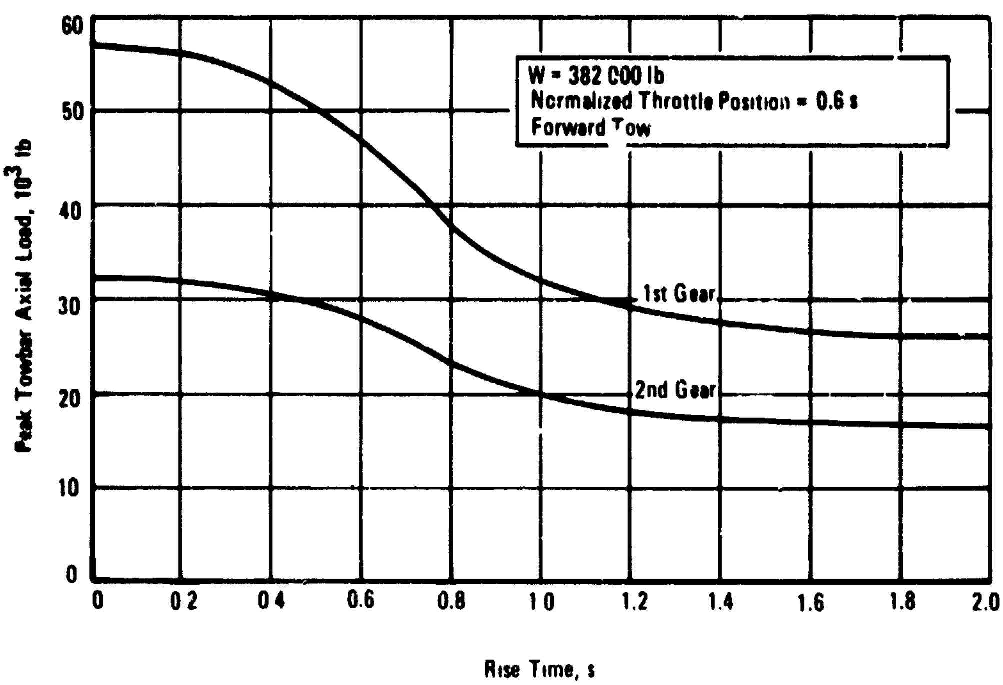

Figure 3-8. Variation of Towbar Load with Rise Time

time. These results are for a first gear start. The corresponding peak loads for a second gear start are 30,300 and 25,990 pounds. These results are more in line with observed test results.

In Figure 3-9, the airplane weight is varied for a nominal condition of 0.6 throttle position and 1.0 second rise time. The dashed line in Figure 3-9 shows a linear relationship between towbar load and airplane weight, while the solid curve represents the analytical results. From Figure 3-9 it can be seen that a fixed throttle position yields a peak towbar load that varies only slightly with airplane gross weight.

Since it is felt that a tug operator would be inclined to accelerate up to a desired velocity at a nearly fixed rate of acceleration, the program also allows inputting a specified curve of acceleration versus time. The general form of this curve is shown in Figure 3-10.

TC and TD are input constants defining the transition times and period of steady acceleration. The transitions use (1-cos) shaped curves. The acceleration level A is not input, but rather the desired final velocity is specified and A is calculated in the program. With the desired acceleration specified by Figure 3-10, the program computes at each time the required tow vehicle thrust, and compares this to the full-throttle thrust available as a function of velocity. The ratio of desired/available thrust is called TPREQ (throttle position required), and in this analysis mode is an output quantity rather than an input. This response history is an approximation of the throttle application required by the tug operator to achieve the desired acceleration history.

For the analytical investigation, a nominal acceleration curve is chosen. This curve yields a final velocity of 3.5 mph after 9 seconds (TC=TD=3 sec), with a maximum acceleration rate of 0.0266 g's. This value is a moderately high acceleration rate that is comparable to the initial forward pull on Test Run F-3 at LAX. For comparison, Reference 2 recommends a maximum tow vehicle acceleration rate during towing of 0.042 g's and a maximum towing velocity of 5 mph. Therefore, the nominal condition chosen is comparable to the highest acceleration rate observed during the LAX tests, but is well below

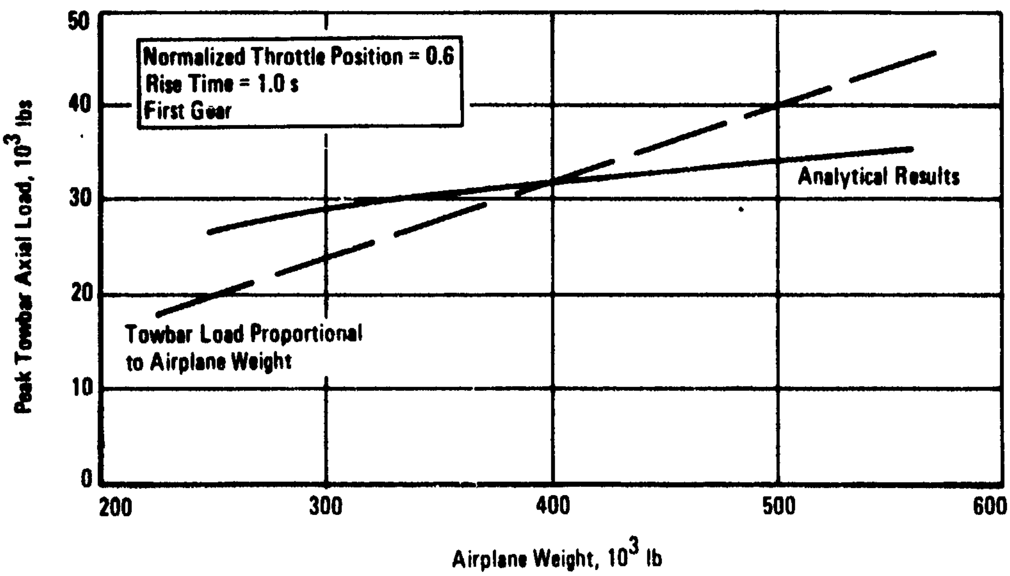

Figure 3-9. Variation of Towbar Load with Airplane Weight

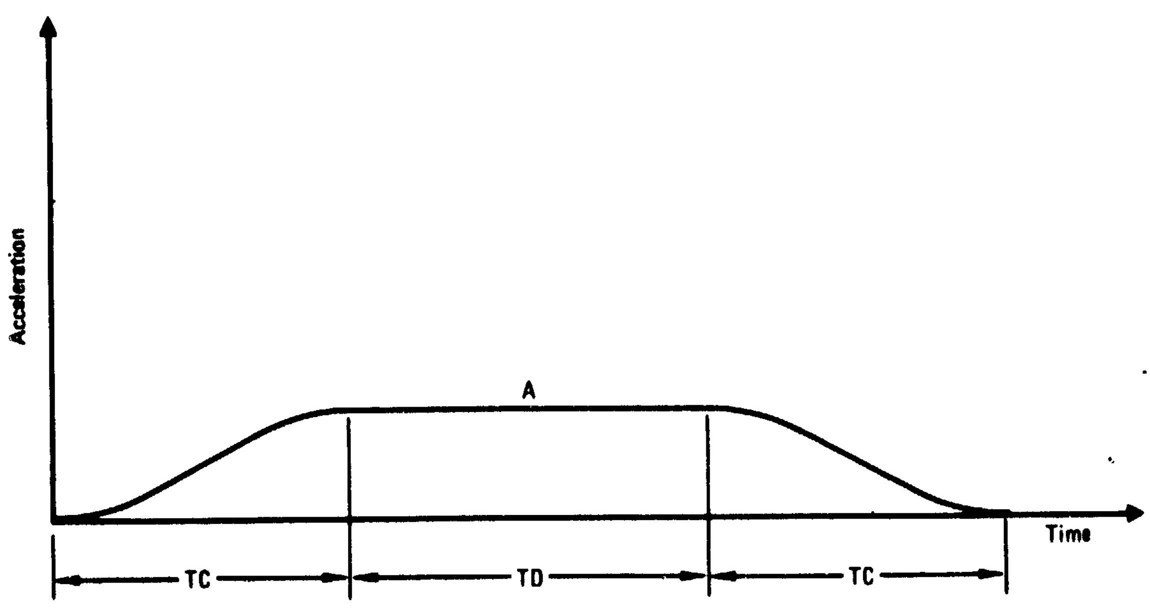

Figure 3-10. Generalized Acceleration Input Curve

the allowable maximum recommended by the manufacturer of the towbar. The nominal airplane weight is 382,000 pounds with a cg position of 25.8% MAC, based on average test values from Table 2-1.

Figures 3-11 through 3-13 show histories of airplane velocity (VXAP), towbar axial load (FTB) and required throttle position (TPREQ), respectively. Figure 3-11 shows both the airplane and tow vehicle velocities, the latter oscillating somewhat about the former. Both velocities approach the final steady value of 3.5 mph in a smooth fashion resulting from specifying the acceleration curve of Figure 3-10. Also shown in Figure 3-11 is the velocity history from Test Run F-3, during the forward pull. Note that the nominal analytical condition is a reasonable approximation of Run F-3. Figure 3-12 shows the analytical towbar axial load history with a peak value of 18,400 pounds, as well as the axial load from Test Run F-3.

It should be noted that the nominal condition analyzed is not intended to correlate exactly with Test Run F-3, but is chosen only as a resonable base point for parameter variation studies. In Figure 3-12 it can be seen that the test results peak earlier and at a lower value, and that the analytical results exhibit less damping than the test results. However, the frequencies in each case are in the order of 1.15 Hz, and the general shapes of the curves agree well enough so that the nominal analytical case can be considered as a representative basepoint condition for parameter variation studies.

Figure 3-13 shows the time variation of throttle position that the tug operator would have to employ to achieve the acceleration history specified. During an actual tow, a tug driver naturally would not follow every wiggle on the curve, but would use a smoothed version of the curve in Figure 3-13. The large decrease from 6.5 to 9 seconds occurs as the driver ramps out the acceleration rate to hold the final steady velocity. The final steady throttle position is that required to maintain 3.5 mph with the rolling friction used in the base case (0.015).

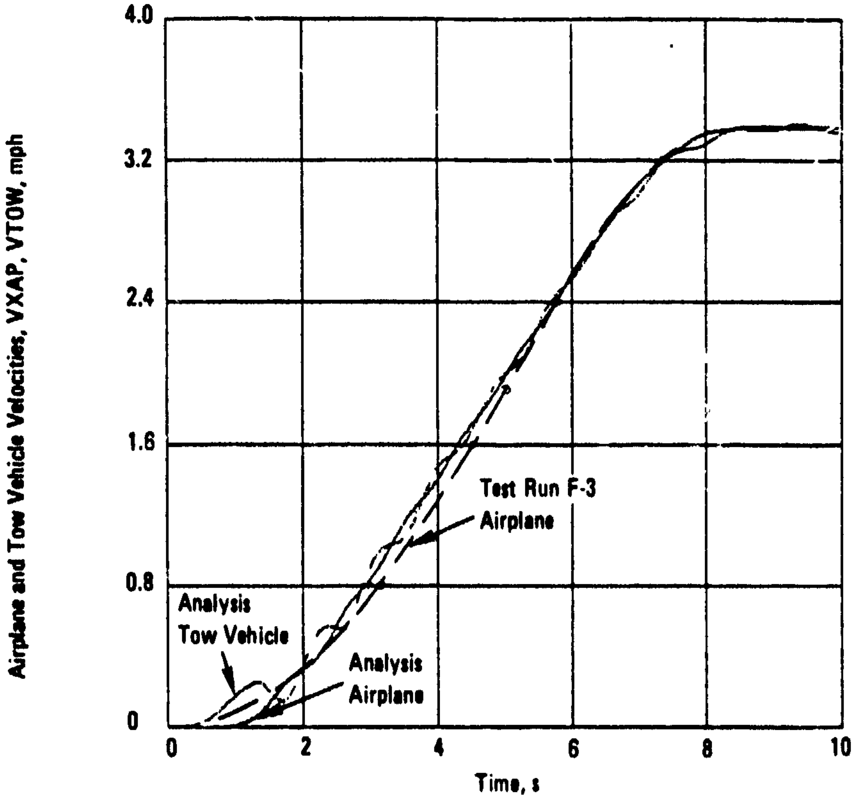

Figure 3-11. Basic Analytical Case, Velocity Histories

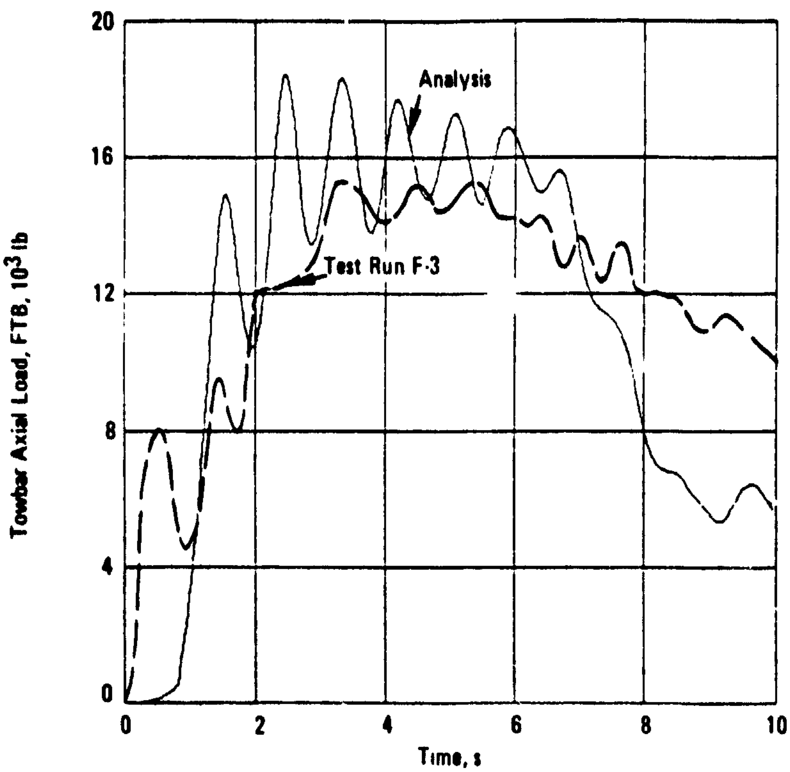

Figure 3-12. Basic Analytical Case, Towbar Axial Load

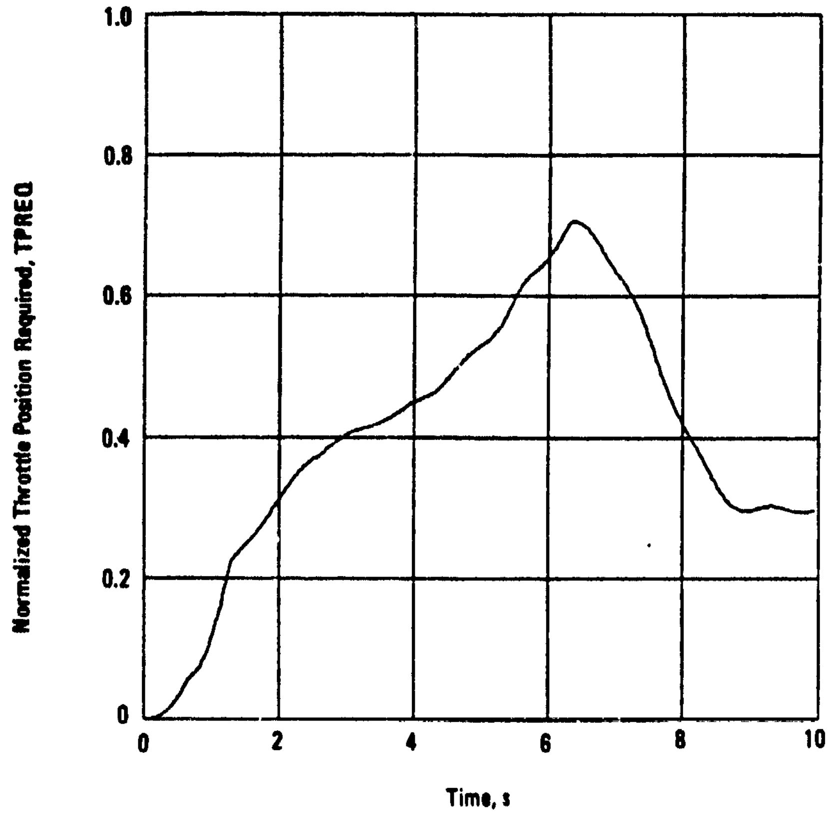

Figure 3-13. Basic Analytical Case, Throttle Position Required

Parameter variations about the base case were performed for the following variables:

- VF, final velocity desired (3.5 mph)
- W, airplane weight (382,000 pounds)
- MU, rolling friction coefficient (0.015)
- CG, airplane cg position (25.8% MAC)
- DS, mechanical backlash in the towbar-hitch connection (0.405 inches)
- BCH, damping in the cushioned-hitch (279 pound-sec/in)

The values for the nominal base case are shown in parentheses. Figures 3-14 and 3-15 show the variation of peak and final steady towbar loads and throttle position, respectively, with final velocity. As the final velocity increases, the steady acceleration level increases since the time span in the acceleration time history input curve (Figure 3-10) was not changed. Therefore, the peak towbar load increases, but the final steady value

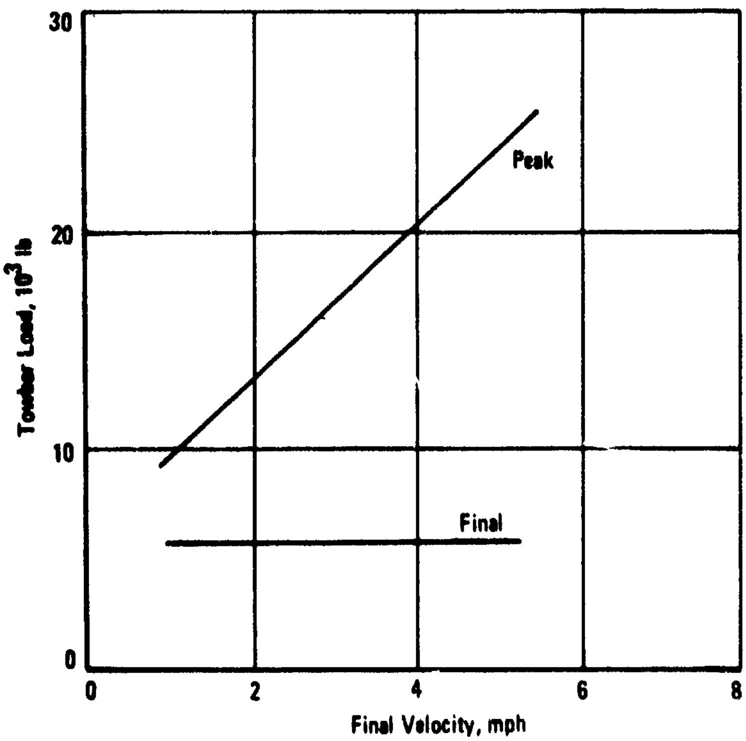

Figure 3-14. Variation of Towbar Load with Final Velocity

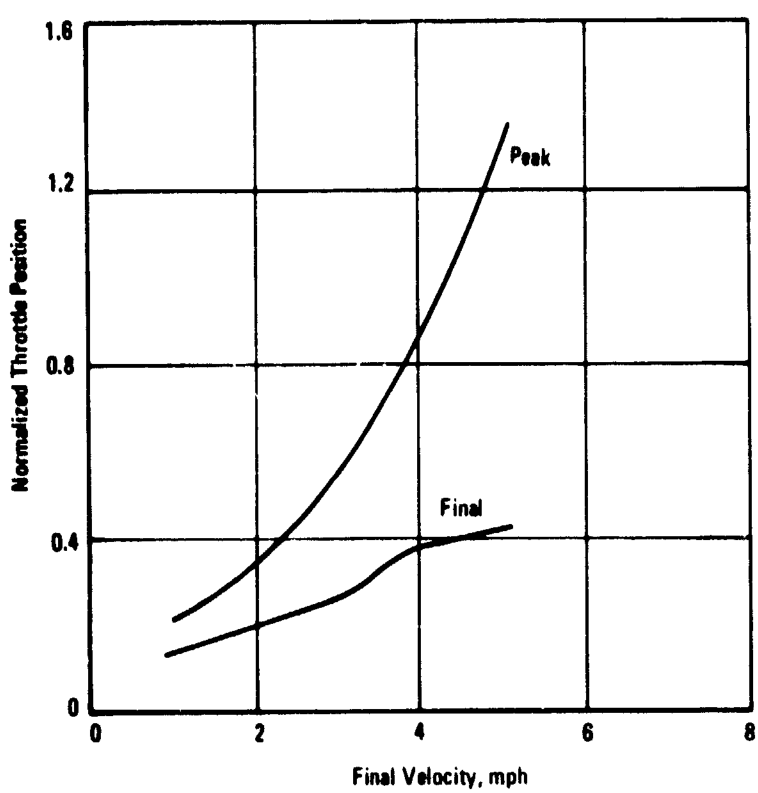

Figure 3-15. Variation of Throttle Position with Final Velocity

remains constant. (The final value corresponds to zero acceleration, so only the total rolling drag must be overcome). In Figure 3-15, both the peak and final throttle position (TPREQ) increase. The increase in final TPREQ is due to the lower thrust available at higher velocities, while the actual thrust required remains constant. At velocities above 4.3 mph, TPREQ peak is greater than 1.0. For these velocities, the airplane cannot be accelerated up to speed in the 9 seconds used in the analysis. Therefore, above 4.3 mph the airplane would take longer than 9 seconds to attain its steady velocity, and the peak towbar loads would be less than shown in Figure 3-14.

Figures 3-16 and 3-17 show the variation in responses with airplane weight. As would be expected, both towbar loads and TPREQ vary linearly with airplane weight, with towbar loads being directly proportional to airplane weight. This is in contrast to the results shown in Figure 3-9, which are based on a constant throttle position input. Figures 3-18 and 3-19 show the variations with rolling coefficient of friction (MU). Once again the final steady values of towbar load and TPREQ vary linearly with MU, but the dynamic peak values show a slight nonlinearity at high MU values. Friction coefficients greater than 0.032 prevent accelerating the airplane to 3.5 mph in 9 seconds.

Figures 3-20 and 3-21 show the sensitivity of the results to cg position. The peak towbar load shows a slight increase with aft cg position, and a pronounced increased at the forward limit of 16 percent MAC. Figure 3-22 shows the response history of towbar load for the 16 percent MAC cg case. Note that this is entirely different in character from the base case shown in Figure 3-12, with large dynamic responses from 5 to 10 seconds. Figure 3-23 shows the corresponding response history for nose gear strut compression. This curve shows large excursions in the range from 12 to 17 inches, with the strut motions being in phase with the towbar loads. For the basic case, the strut motions never go outside the range from 13 to 14 inches, and are not in phase with the towbar loads.

The fore-aft natural frequency of the airplane/tow vehicle system is a function of two springs, the cushioned-hitch and the fore-aft nose gear stiffness. The former varies nonlinearly with towbar axial load, and the

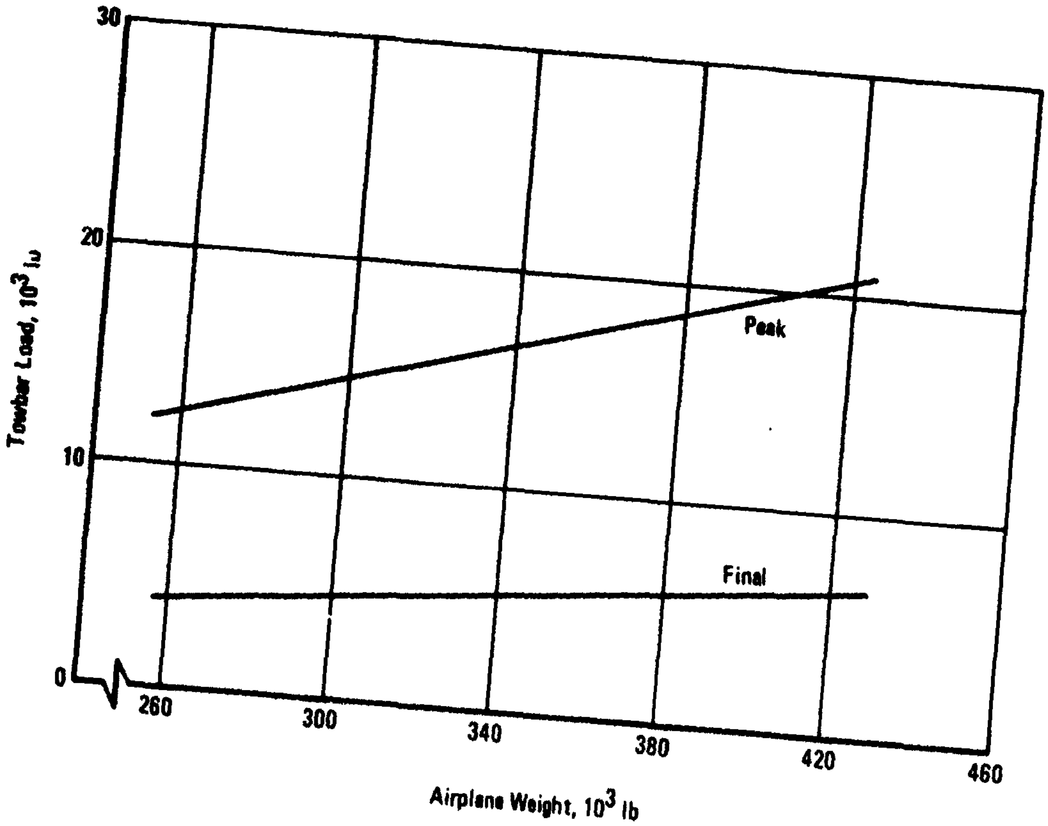

Figure 3-16. Variation of Towbar Load with Airplane Weight

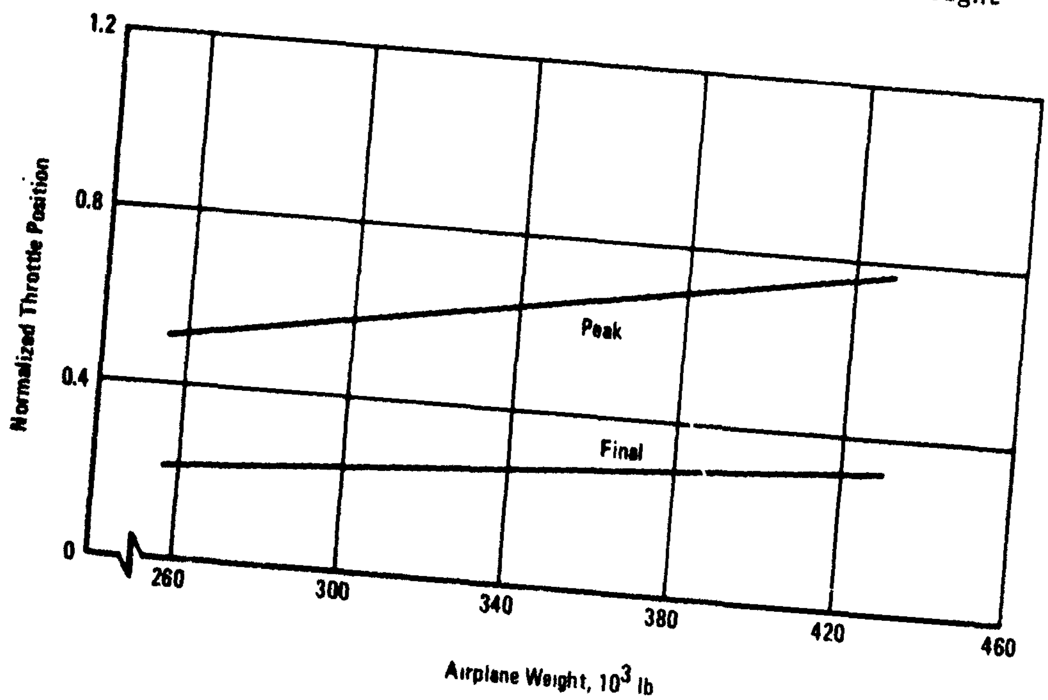

Figure 3-17. Variation of Throttle Position with Airplane Weight

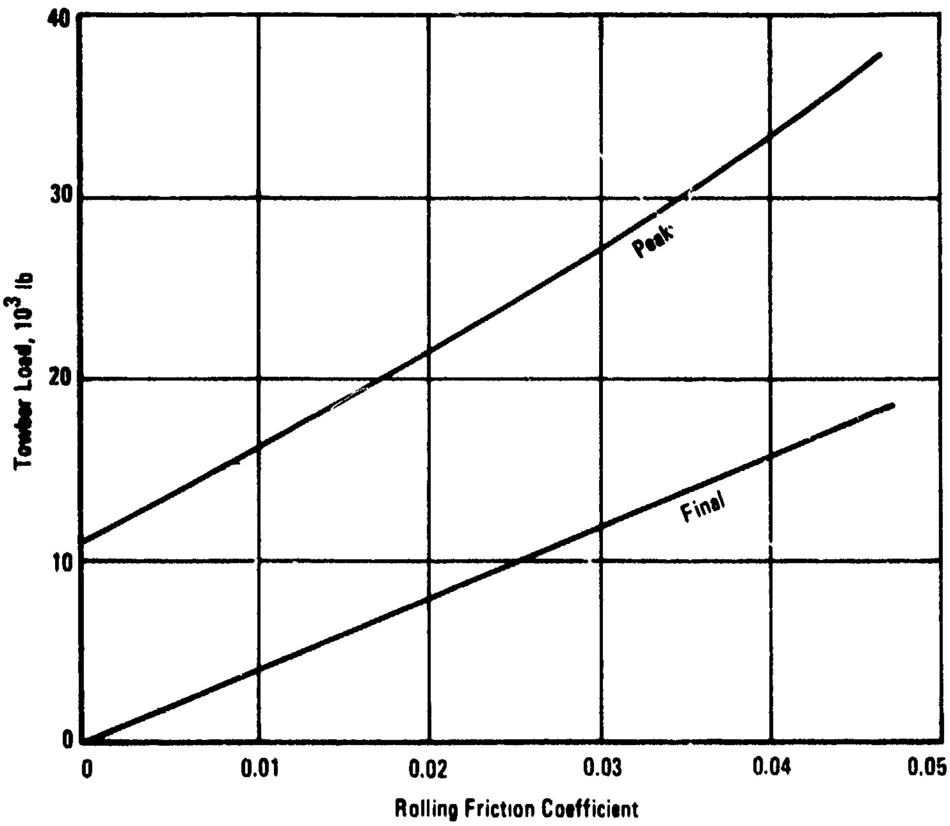

Figure 3-18. Variation of Towbar Load with Rolling Friction

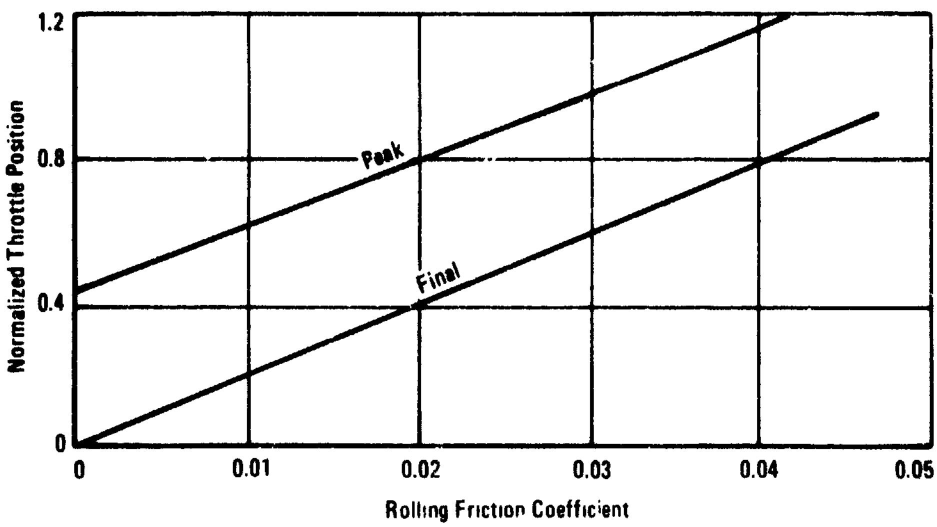

Figure 3-19. Variation of Throttle Position with Rolling Friction

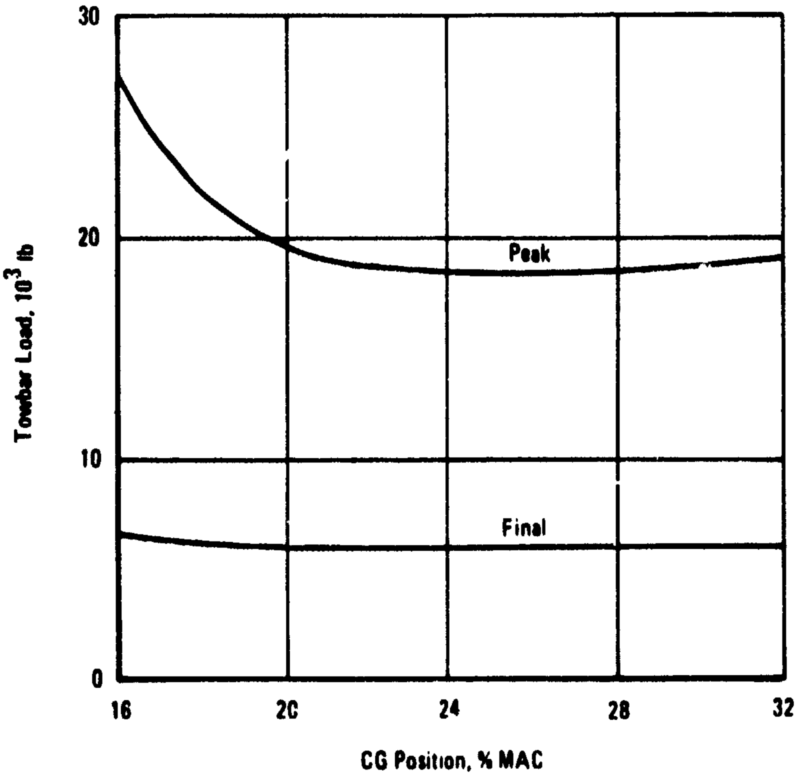

Figure 3-20. Variation of Towbar Load with CG Position

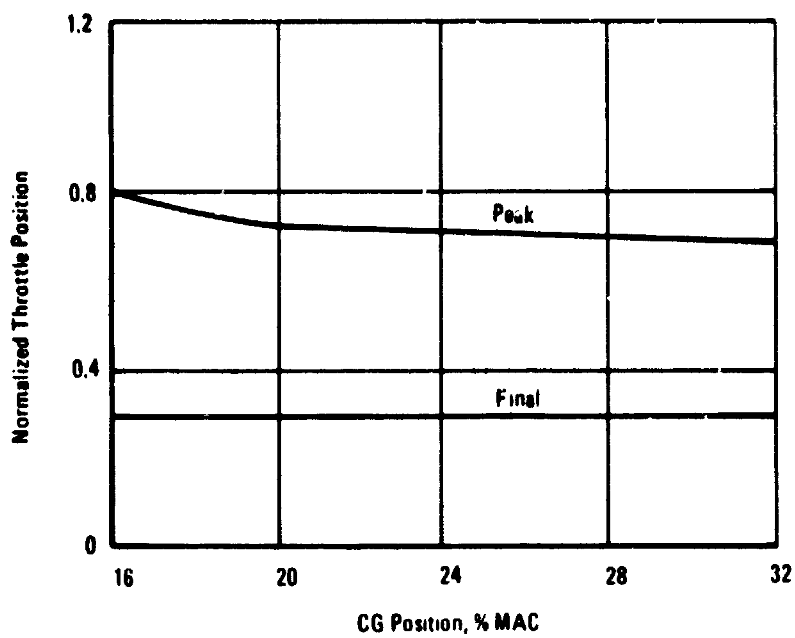

Figure 3-21. Variation of Throttle Position with CG Position

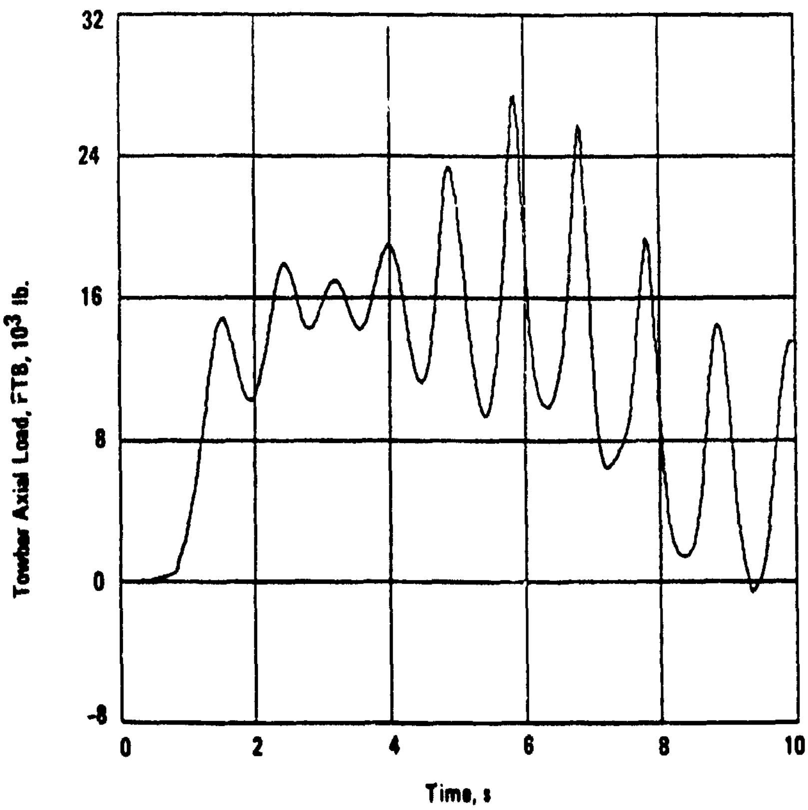

Figure 3-22. Towbar Load History, Forward CG Case

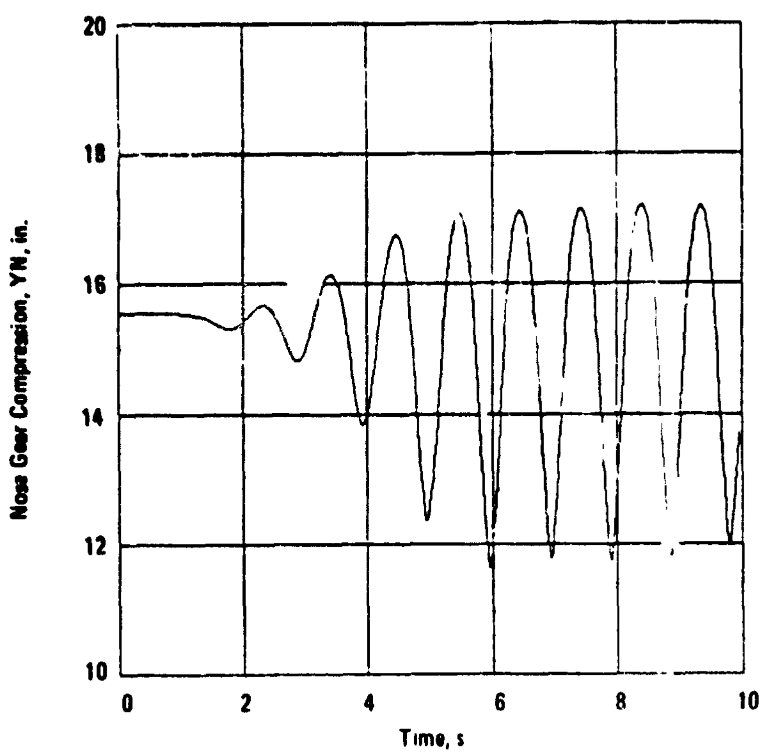

Figure 3-23. Nose Gear Compression History, Forward CG Case

latter varies with nose gear extension. In addition, the airplane pitch natural frequency is a function of nose gear extension (due to the nonlinear air curve). For the forward cg condition, the airplane pitch mode and the airplane/tow vehicle fore-aft mode respond in phase at the same frequency (1.0 Hz), which greatly accentuates the dynamic response resulting in large towbar axial load oscillations. At different airplane and/or tow vehicle weights, these frequencies could coincide at other cg positions. The test results at Palmdale do not show any increase in towing loads at forward cg position. However, the most forward cg tested was 19.8 percent MAC, and from Figure 3-20 the results at this cg position would be expected to be normal. More forward cg positions could not be tested due to difficulties in achieving extreme cg positions with the flight-test airplane.

The sensitivity of the results to backlash at the towbar/hitch interface is shown in Figure 3-24. There is only a slight (7 percent) increase in peak towbar axial load at a backlash twice the nominal value. This would correspond to a pull-tow with the towbar initially compressed just enough to take up all the backlash. (The computer program is coded so that the towbar/hitch starts in the center of the backlash region.)

Figure 3-25 illustrates the effect of varying the damping constant used for the cushioned-hitch. As described previously, the cushioned-hitch operates by compressing eight 6 inch O.D. Adiprene rubber springs. This provides a nonlinear spring and some unknown damping characteristic. The program models the damping as linear, with a nominal value chosen to provide 10 percent damping for the airplane/tow vehicle fore-aft mode. From Figure 3-25, it can be seen that 0 damping would raise the peak towbar load 9 percent above the nominal value, and that 3.2 times the nominal value (BCH=900), reduces the peak load 8 percent.

While the magnitude of the peak towbar load is not drastically influenced by the damping constant, the characteristics of the time-history curves are significantly altered. Figures 3-26 and 3-27 show the towbar responses for the zero damping and BCH=900 cases, respectively. The influence of the higher damping is readily apparent, and the reduced oscillations in

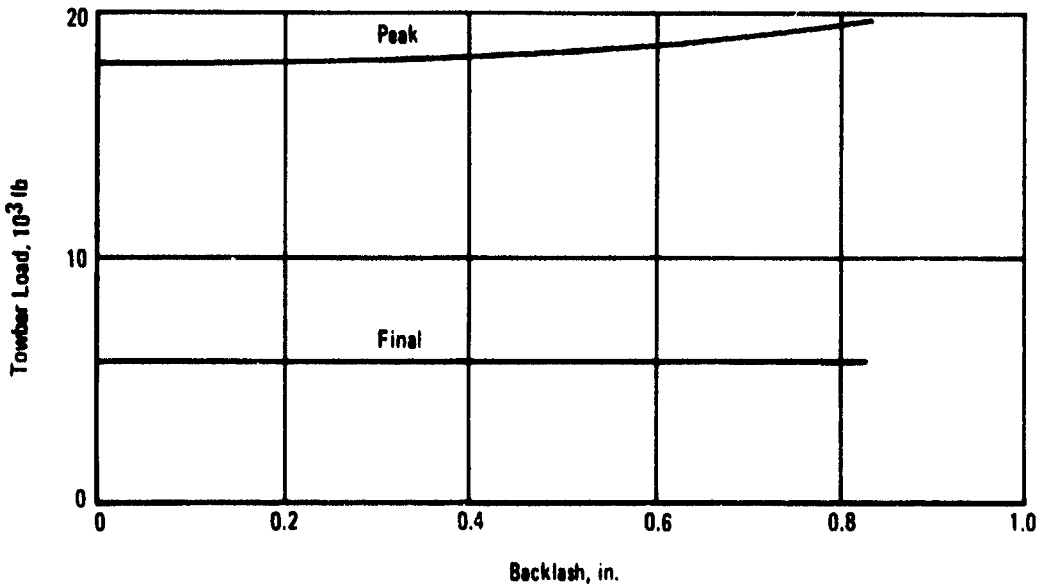

Figure 3-24. Variation of Towbar Load with Backlash

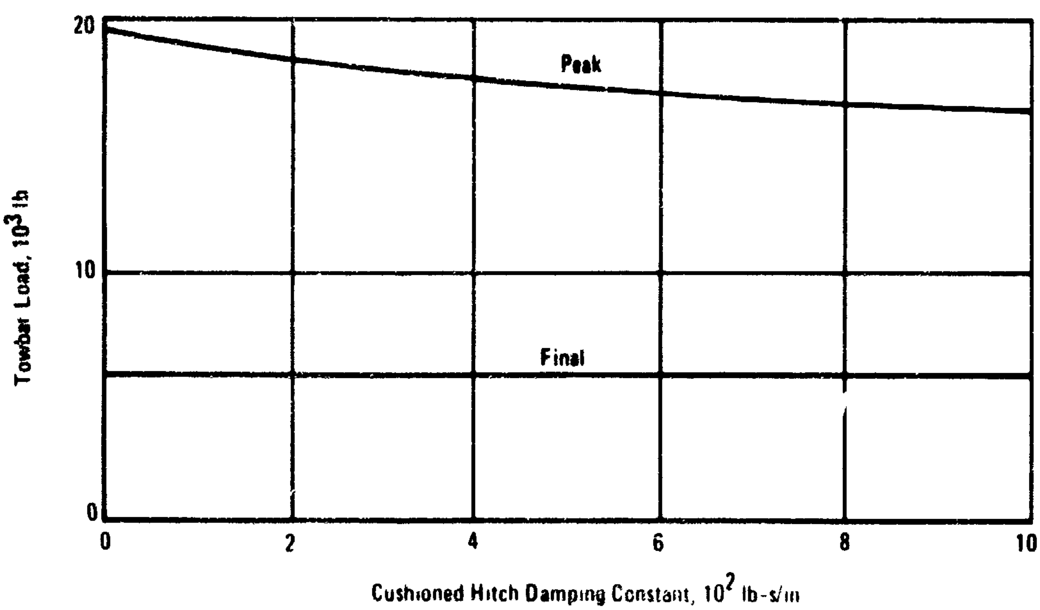

Figure 3-25. Variation of Towbar Load with Damping

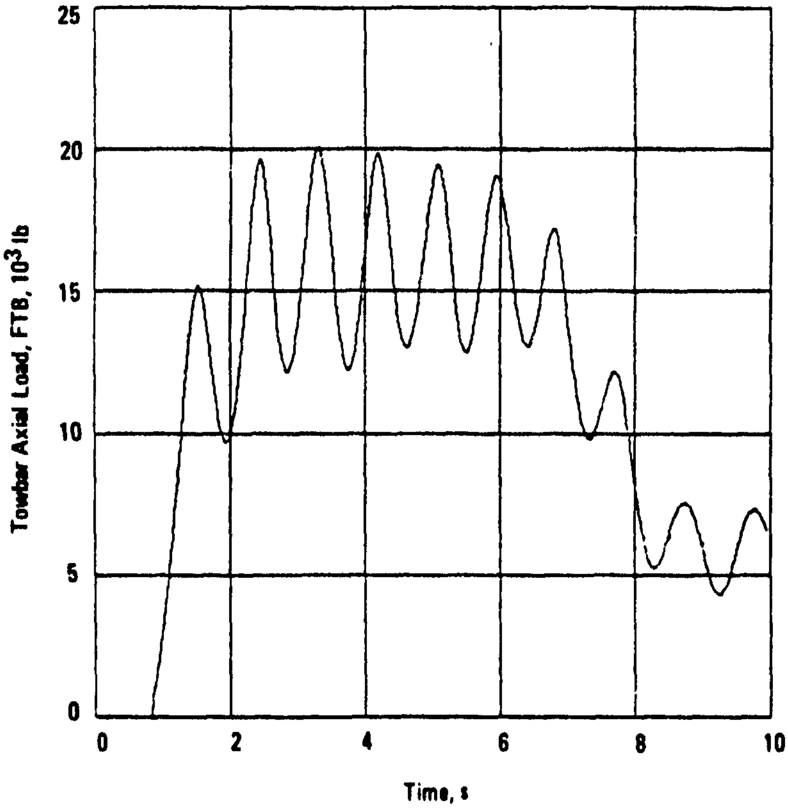

Figure 3-26. Towbar Load History with BCH = 0

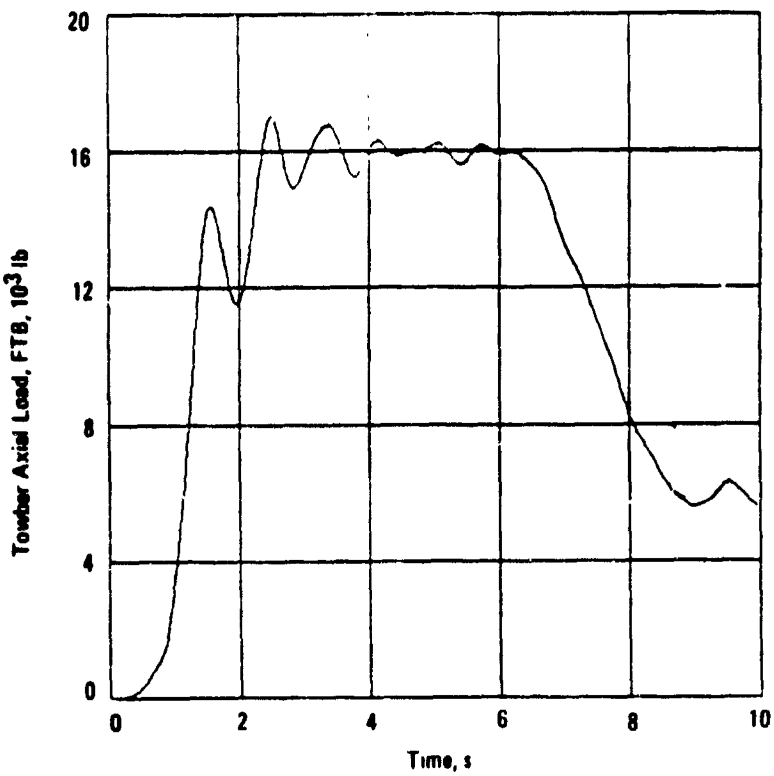

Figure 3-27. Towbar Load History with BCH = 900

Figure 3-27 are comparable to the test data shown in Figure 3-12. Since it is very difficult to estimate the actual damping due to the rubber springs in the cushioned hitch, the higher value may be more realistic.

The towing tests at Palmdale were performed with a Hough T-800S tractor, which is larger and more powerful than the T-500S tug used by TWA at LAX. The T-800S tug also has a conventional hitch, rather than the cushioned-hitch used on the T-500S. In addition to the difference in hitches, the two tugs differ in geometry, weight and engine power curves.

Figure 3-28 shows a plot of the towbar axial load obtained from the CSMP program for a nominal towing condition using the T-800S tug without a cushioned-hitch, along with the towbar load for the same condition using the T-500S tug with a cushioned-hitch. The actual peak load is slightly greater with the cushioned-hitch, but the situation would be reversed if the hitch damping for the cushioned-hitch were doubled. Without the cushioned-hitch, the frequency of the tug/airplane fore-aft mode increases to around 1.9 Hz, compared to 1.1 Hz for the tug with the cushioned-hitch. Also just barely visibile in Figure 3-28 is the presence of a very high frequency mode (around 100 Hz) representing the nose gear unsprung mass and the high towbar stiffness. The cushioned-hitch eliminates this mode.

The results in Figure 3-28 are based on the tug driver attempting to achieve a specified acceleration history. With the T-800S tug, this requires a lower throttle setting than with the T-500S tug (a peak of 45 percent of available power versus 71 percent for the T-500S). On this basis, the mean towbar load will be the same in either case. However, with the more powerful tug the potential exists for developing greater towbar axial loads.

3.3 SUMMARY OF COMPUTER PROGRAM RESULTS

The following implications are drawn from the analytical towing loads model computer results:

- Very large towbar loads are theoretically possible with zero or very small time lag in the tug's applied thrust.
- The time lag actually present greatly reduces the maximum towbar loads that can be attained.

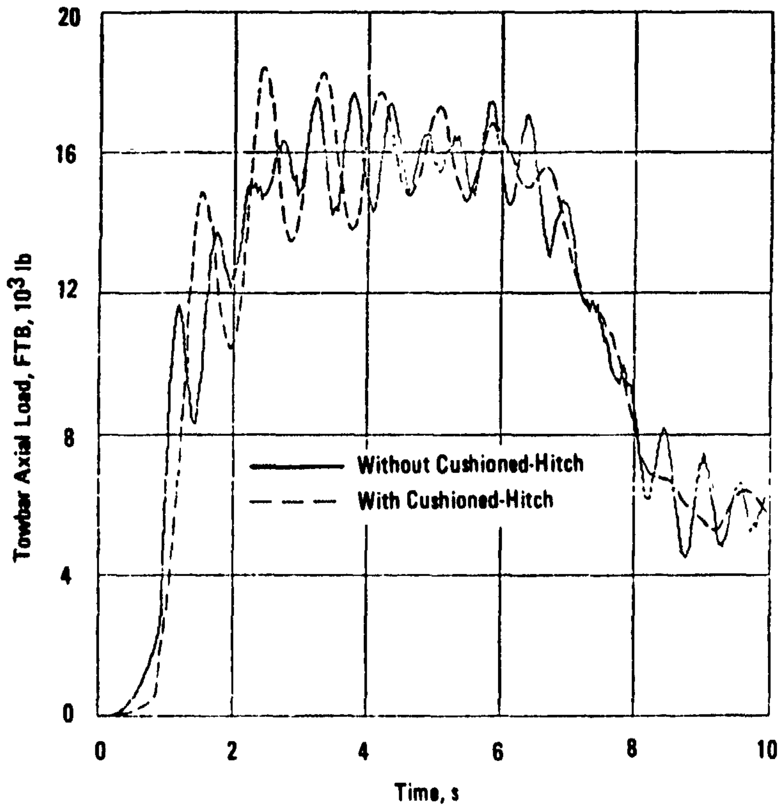

Figure 3-28. Towbar Axial Load with and without Cushioned-Hitch

- For a fixed throttle position input, towbar loads increase only moderately with increased airplane weight.
- For a fixed rate of airplane acceleration, peak towbar loads are directly proportional to airplane weight, and vary linearly with rolling friction coefficient.
- Towbar loads are relatively insensitive to airplane cg position, except at extreme forward cg positions.
- Towbar loads are only moderately affected by towbar/hitch backlash and damping.
- Correlation between analytical and test results is good.

SECTION 4

EXTENDED TOWING FATIGUE LOAD SPECTRUM

The results of the test and analytical studies were used to develop a fatigue load spectrum representing extended towing operations at Boston-Logan. Both the test and analytical results indicated that the towing loads are very sensitive to driver technique, and that normal variations in this factor tend to override variations in airplane weight and other parameters having less effect on towing loads.

For this reason, the Palmdale test data simulating the towing path at Boston-Logan (Runs 1-18) could not be used directly to specify a towing load spectrum. Instead, this data was used in conjunction with the test data at LAX and Dorval to define a statistical variation of towbar loads during normal towing operations. The test results indicate that the significant peak towing loads are associated with starting and stopping the airplane. Therefore, the statistical towing load data is developed in terms of the number of load peaks per start/stop cycle, where a start/stop cycle is defined as an operation in which the airplane velocity varies from zero up to a finite value and back to zero.

Figure 4-1 shows a plot of the peaks per start/stop cycle (ordinate) exceeding a given towbar axial load level (abscissa). Separate curves are shown for both forward and aft acting loads. Towbar loads less than 10,000 pounds are ignored since they contribute nothing to the fatigue damage of the nose gear. Table 4-1 is a summary of the towing data used to derive the spectrum in Figure 4-1. The special test conditions at Palmdale (Runs 19-25) were not included in the development of Figure 4-1. Examining the overall averages

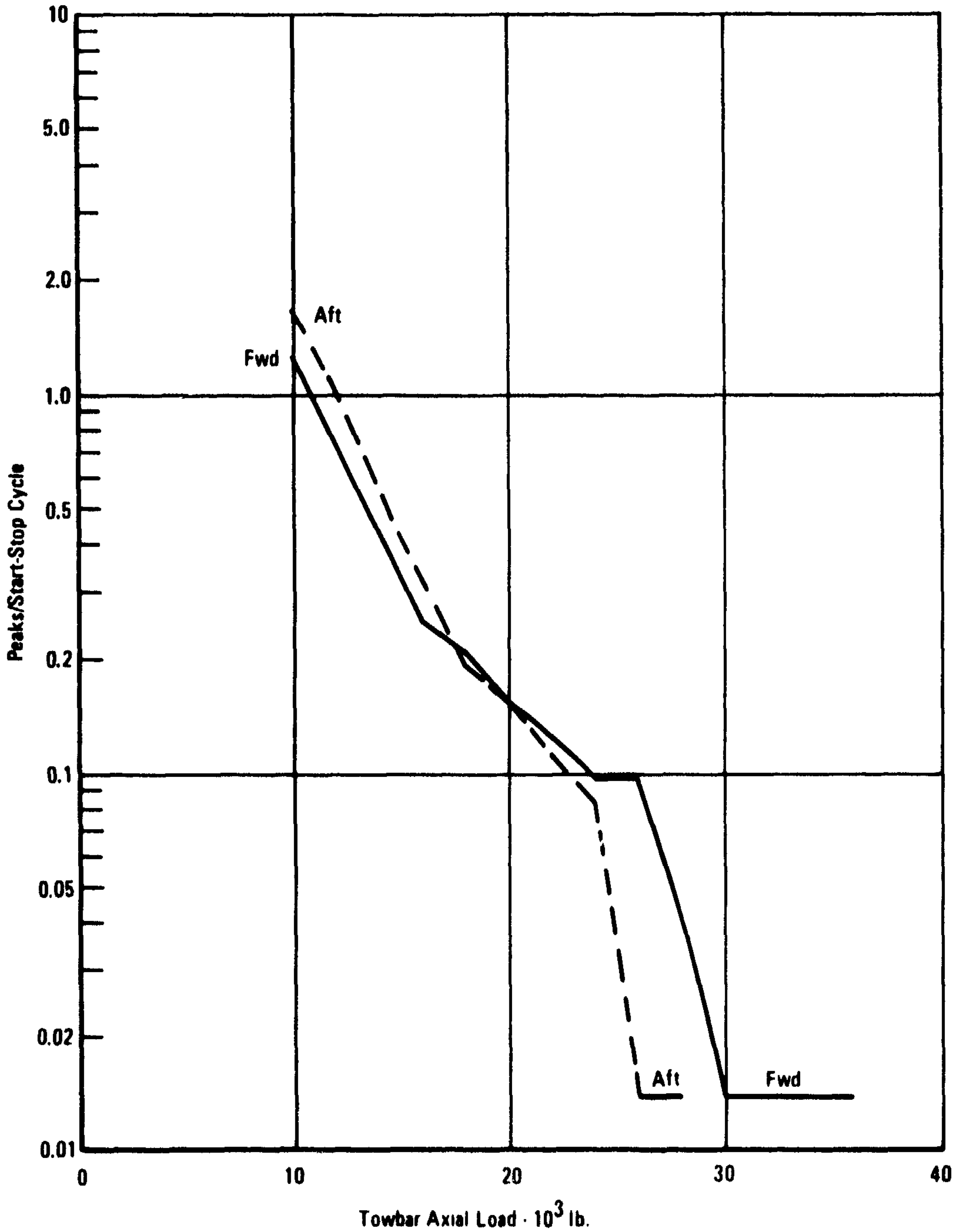

Figure 4-1. Towing Load Spectra

TABLE 4-1. TOWING TEST DATA SUMMARY

	Number of Tows	Number of Start/Stop Cycles	* Number of Peaks	No. of Non-zero Steering Angles	Peaks per Start/Stop Cycle	Start/Stop Cycles per Tow
Operational:						
- LAX	16	28	105	27	3.75	1.75
- Dorval	7	9	38	**	4.22	1.29
- Palmdale	14	23	25	9	1.09	1.64
Total	37	60	168	36+	2.8	1.62
Maintenance:						
- LAX	2	4	18	10	4.50	2
- Dorval	4	8	24	**	3.00	2
Total	6	12	42	10+	3.50	2
Totals						
LAX	18	32	123	37	3.84	1.78
Dorval	11	17	62	**	3.65	1.55
Palmdale	14	23	25	9	1.09	1.64
Overall Totals	43	72	210	46+	2.92	1.67

*Peaks of magnitude less than 10,000 pounds are excluded.

**Steering angle not measured at Dorval.

TABLE 4-2. STEERING ANGLE DISTRIBUTION

Steering Angle, Degrees	Fraction of Tows
0	.68
5	.085
8	.094
14	.104
20	.028
28	.009
Total	1.000

in Table 4-1, there are about 1.7 start-stop cycles/tow and 2.9 peaks/start-stop cycle. Also shown in Table 4-1 are the number of peaks which occur simultaneously with a non-zero steering angle. Examination of the steering angle data results in the distribution of steering angles shown in Table 4-2. Approximately two-thirds of the peak loads occur with zero steering angle, with the remaining one-third distributed at angles not exceeding 28 degrees.

The load spectra in Figure 4-1 include both maintenance and operational towing. Although one might expect the loads to be lower during maintenance towing due to the lower airplane weights, the test results from Section 2 do not indicate that this is true. In fact, at both LAX and Dorval some of the largest towbar loads occurred during maintenance towing at light weights. The reason for this is the variation in tug driver technique. The drivers tend to be more gentle with the operational tows and operate at somewhat lower velocities than the maintenance tows. The higher velocities associated with maintenance towing provide more opportunity for shifting gears with the tug, which is a potential source of high dynamic towing loads. Since the amount of maintenance towing data is rather limited, it was decided to lump together the maintenance and operational towing loads to form the overall spectra shown in Figure 4-1.

The frequency of exceedance curves in Figure 4-1 are representative of normal towing operations, since the data are obtained from normal operations. The only distinction between normal and extended towing is in the selection of a number of towing start/stop cycles per flight used in conjunction with Figure 4-1. In this regard, even a long towing operation (one mile or more) may consist of only one or two start/stop cycles. From a fatigue loading viewpoint, the long towing operation may be no more damaging than a conventional operation having the same number of start/stop cycles. This situation stems from the fact that the significant towing loads are associated with starting and stopping the airplane. However, long tow operations involve the hazard of unplanned start/stop cycles to allow for traffic, so that in general long operations will involve more start/stop cycles per tow.

To represent extended towing at Boston-Logan, a towing rate of five start/stop cycles per flight is used. This figure consists of three planned operational start/stop cycles per flight, one maintenance start/stop cycle per flight and one unplanned start/stop cycle. The three operational cycles involve a push back and forward pull during departure (2 cycles) and a forward pull (1 cycle) during arrival. The maintenance towing involves a round trip operation consisting of 6 start/stop cycles, occurring once every six flights.

The rate of five start/stop cycles per flight is representative of an airplane operating entirely at airports using extended towing operations similar to those proposed at Boston-Logan, and represent a maximum exposure level that would never be achieved if Boston-Logan were the only airport to utilize extended towing. By way of comparison, normal towing operations would consist of one or two cycles during departure, zero cycles during arrival and one cycle/flight for maintenance, for a total of two or three cycles/flight. Normal towing utilizes the loads in Figure 4-1 but at a reduced rate of two or three cycles/flight versus five cycles/flight for complete extended towing. An actual airplane operating out of Boston-Logan would be exposed to an average rate somewhere between two and five start/stop cycles per flight.

The towing loads for extended towing replace a portion of the towing loads in the overall ground handling fatigue load spectrum. In the basic ground handling load spectrum for the L-1011, there are a total of 12 turns per flight at different turn radii representing typical maneuvering during ground taxiing. Three of these turns are at a minimum turn radius of 30 feet. It is assumed that the extended towing spectrum replaces two of these turns (one during departure, one during arrival), leaving one 30-foot radius turn and 10 turns total per flight.

Figure 4-2 shows the same spectra replotted on a per flight basis, using five start/stop cycles per flight for extended towing. These spectra are shown as dashed lines in Figure 4-2. Also shown for comparison are the spectra for towing loads used in the design of the L-1011-1.

For the aft acting loads the design spectrum is more severe than the extended towing spectrum, indicating a rather conservative estimate of design towing loads. For the forward loads, the design spectrum is limited to maintenance operations only, wherein the lower airplane weights preclude large towing loads (according to the analytical methods used to develop the original design spectrum). During the towing tests, more severe forward loads were observed, due in part to the fact that operational towing (at high airplane weights) includes forward pulls that were not included in the original design spectrum, and also due to the aforementioned high towing loads at light weights during maintenance towing. A spectrum representing normal towing operations, based on the test results of this program, would have the same shape as the extended towing spectrum shown in Figure 4-2, but shifted downward in frequency by a factor of 2/5 = 0.4.

The spectra in Figures 4-1 and 4-2 are for towbar loads acting in the direction of the towbar. Since the steering angles coincident with peak towbar loads (Table 4-2) are small (less than 4 percent of the peaks occur with steering angles above 14 degrees), the load spectra in Figures 4-1 and 4-2 essentially are valid for fore-aft loads in airplane fixed axes.

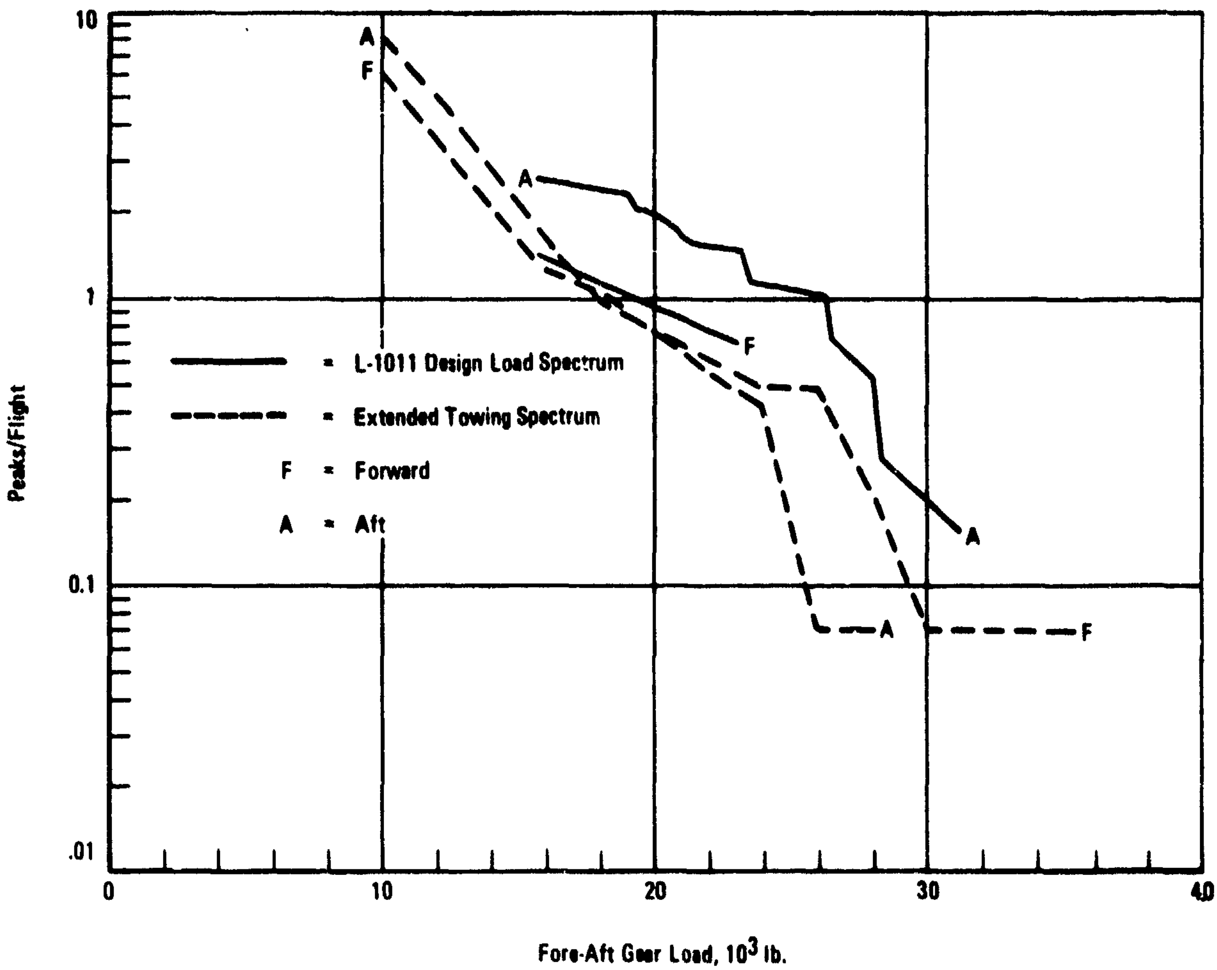

Figure 4-2. Towing Load Spectra, per Flight Basis

The corresponding side load spectrum is not shown because the peak load contained therein is (36,000 pounds) (sin 28 degrees) = 16,900 pounds. Prior stress analyses of the nose landing gear indicate that side loads less than 20,000 pounds cause no fatigue damage. The original towing load design spectrum for the L-1011 contains higher side loads (up to 24,000 pounds), resulting from the assumption that peak towbar loads occur simultaneously with large steering angles in the order of 45 degrees. While steering angles in the 40 to 50 degree range were frequently encountered during the test program, they never occurred simultaneously with large towbar loads. For example, the peak axial towbar load during the constant radius towing turns at Palmdale is 16,500 pounds (Table 2-7, Runs 21, 22).

The towing load spectrum is derived under the assumption that accepted normal towing procedures are always followed. In particular, it is assumed that the nosewheel steering lockout pin is properly inserted during each tow. Failure to insert the lockout pin would result in the steering system not being bypassed during towing. This in turn would generate large loads in the torque arms, steering collar and steering actuators. During the test program, the steering lockout pin was always properly installed.

SECTION 5

FATIGUE LIFE STRESS ANALYSIS

5.1 FATIGUE ANALYSIS METHODOLOGY

The stress analysis of the nose landing gear and support structure is based upon the fatigue load spectrum for the basic L-1011-1, at a maximum gross weight of 468,000 pounds. The complete spectrum covers all phases of ground handling, including landing impact, landing rollout, takeoff roll, dynamic taxi, braking, steering and towing. For the extended towing fatigue analysis, the towing portion of the design spectrum is deleted and replaced by the extended towing spectrum developed in Section 4 herein. In addition, two of the total of 12 turns per flight are deleted from the spectrum, since the extended towing now covers these turns at Boston-Logan.

The fatigue life stress analysis is performed for the following spectra.

a. Design Towing - This is the spectrum for towing used for the basic design of the L-1011, as shown in Figure 4-2.

b. Normal Towing - This is the spectrum using loads based on the current program test results, with a frequency of 2 start/stop cycles per flight to represent normal towing operations.

c. Extended Towing - This spectrum represents extended towing operations with a frequency of 5 tows per flight, which would be appropriate if all operations were performed at airports requiring extended towing with the same towing pattern as required at Boston-Logan. This spectrum is shown in Figure 4-2.

d. Extended Towing, Steer Collar - This is the same as spectrum C except that the towbar loads are applied at the steer collar rather than at the tow lugs (Figure 5-1). This spectrum is analyzed only to determine the potential reduction in fatigue damage due to a relocation of the towbar attach point. This concept is discussed further in Section 6.

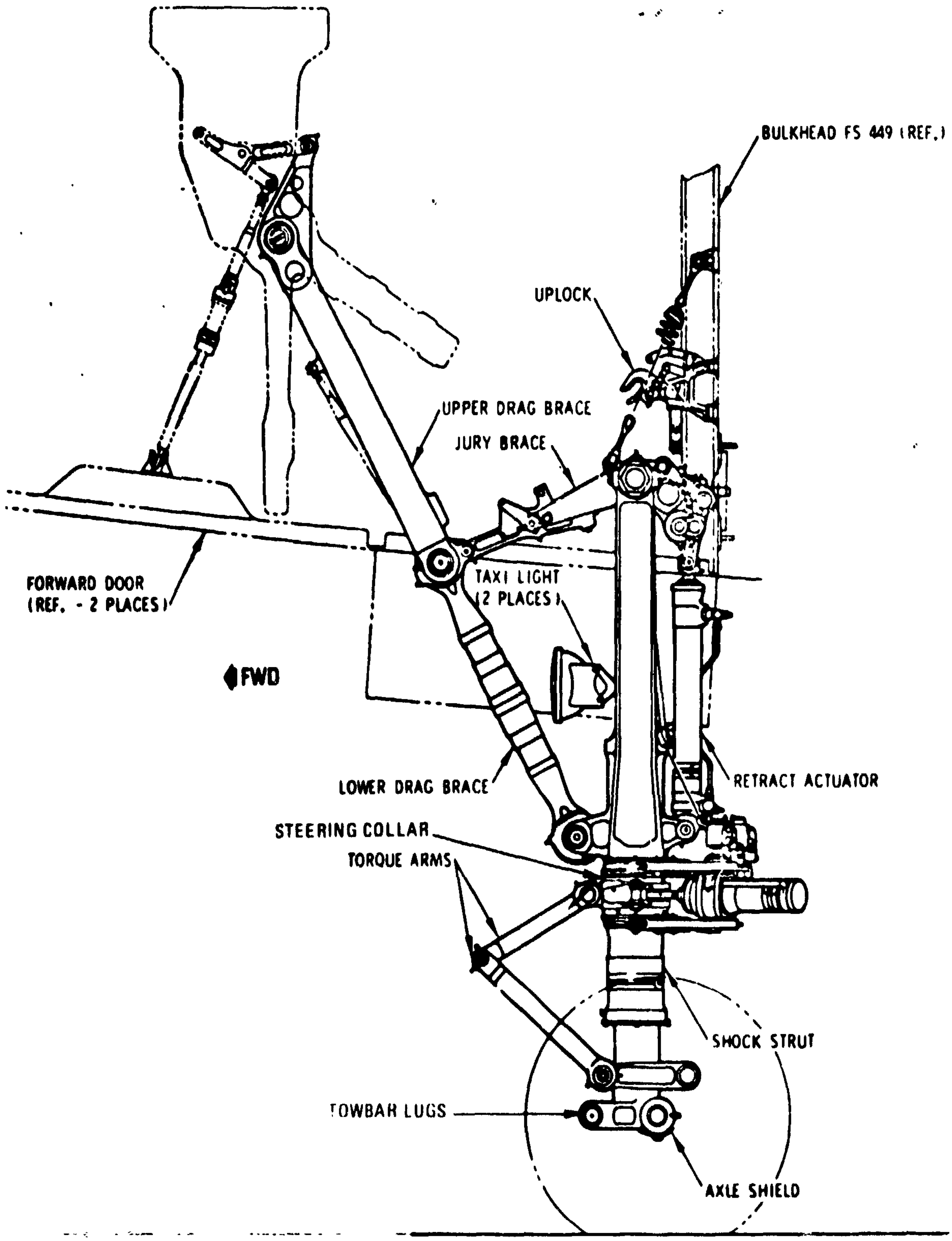

Figure 5-1. L-1011 Nose Landing Gear Arrangement

As discussed in Section 4, the nose gear side loading for the extended towing spectrum is not critical. Therefore, the stress analysis focus on the drag brace and related structure which are sensitive to fore-aft loading at the towbar lugs. Figure 5-2 shows a cumulative load spectrum for the drag brace axial load. Curve 1 is the basic design spectrum, Curve 2 is the design spectrum with the basic towing loads and two steering turns removed, and Curve 3 is the final extended towing spectrum. The loads in Figure 5-2 include all ground handling conditions. Comparison of Curves 1 and 3 reveals that the extended towing spectrum is more severe in the compression direction at high load levels and also in the high cycle, low load region of the curve. Drag brace compression corresponds to forward towing loads. In the drag brace tension direction (aft towing loads), the extended towing spectrum is somewhat less severe than the design spectrum. Also shown in Figure 5-2 is the Ground-Air-Ground (GAG) cycle magnitude for the extended towing spectrum. The GAG load range is defined as the magnitude of loading that occurs once per flight.

Figure 5-2 gives no information regarding the sequence in which positive and negative loads occur. Since a part's fatigue life is sensitive to the magnitude of the load range (maximum tension to maximum compression), it is necessary to specify combinations of positive and negative loads that occur together. Based on the actual load histories of the towing test results, load sign reversals occur for 25 percent of the peak loads. This means that for one-fourth of the peak towing loads, a positive peak is followed immediately by a negative peak (of different magnitude) or vice versa. For the remaining three-fourths of the peak loads, the load returns to zero after the peak. This effect is incorporated into the stress analysis by combining the tow loads greater than the GAG cycle level with an opposite sign load at the GAG load level for 25 percent of the loading cycles. The remaining 75 percent of the cycles vary from zero up to the given load level and back to zero. This method is more conservative than letting all cycles range from zero to peak to zero, and is considered to be more representative of the actual loading experienced by the structure. It is Lockheed policy with fatigue analysis to include one cycle per flight of GAG level loading. In Figure 5-2, it can

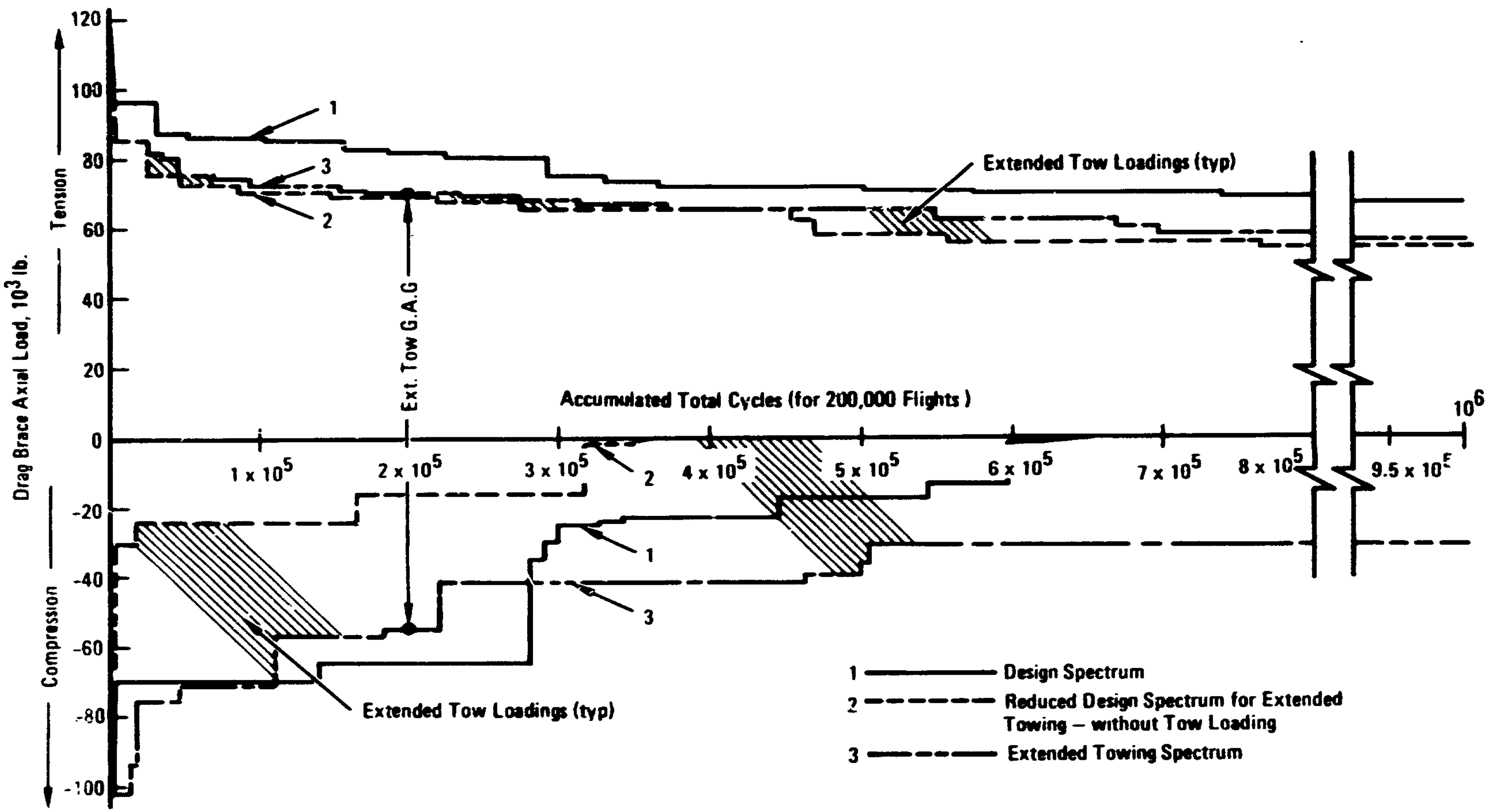

Figure 5-2. Nose Gear Drag Brace Cumulative Load Spectra

be seen that this adds one cycle per flight ranging from 70,400 pounds tension to 56,000 pounds compression on the drag brace. (These loads correspond to tow-bar loads of 25,820 pounds compression and 20,780 pounds tension, respectively.)

The stresses in the various parts of the drag brace system are linearly related to the drag brace axial load, so that Figure 5-2 with appropriate scale factors represents the stress spectrum for all drag brace hardware. The Palmgren-Miner theory of linear cumulative fatigue damage is employed. The stress concentration factor K_T, used in the analysis of each part is conservatively based on the nose gear fatigue test results. A plot of K_T versus calculated damage is made for each point analyzed using the exact test load spectrum. The K_{TEST} for each part is taken as the value of K_T at a damage of 1.0. If a particular part actually failed at the end of the test, K_{TEST} would represent an accurate K_T for that part. For parts that did not fail during the fatigue test, the stress concentration factor determined in this manner is conservative (the actual damage at the end of the test is less than 1.0, corresponding to a K_T less tha K_{TEST}).

5.2 FATIGUE ANALYSIS RESULTS

Table 5-1 presents a summary of the analytically predicted fatigue lives for parts of the nose landing gear and support structure. The calculated lives are shown for the four different towing load spectra defined in the previous section. The item numbers in Table 5-1 are shown in the nose gear illustration in Figure 5-3. The most critical location is the diagonal brace in the BL22 Keelson, shown in Figure 5-4. The upper drag brace attaches at point A, and the gear trunnion at point B. The diagonal brace between A and B has a gap in the center, and is joined with splices using Hi-Tigue protruding shear head fasteners. The brace and splices are made of 7075-T6 aluminum. Figure 5-5 illustrates the tapered splice at the BL-22 diagonal joint.

For the BL-22 diagonal, the fatigue test load spectrum does insufficient damage to determine a meaningful stress concentration factor. The test

TABLE 5-1. CALCULATED FATIGUE LIVES FOR NORMAL AND EXTENDED TOWING

Critical Item	Component	Equivalent Fatigue Life, 10^6 Flights ②			
		Design Towing	Normal Towing	Extended Towing	Extended Towing, Steer Collar
Points Stressed in Tension for Aft Tow Loads:					
① 1	Pin-Drag Brace Knee	1.46	15.9	12.1	16.4
3	Pin-Trunnion, Drag Brace	50.9	59.5	58.6	59.5
8	Pin-Drag Brace, Lower	66.7	66.7	66.7	66.7
18	Drag Brace Assy: Upr. Trun. Socket	.828	4.31	8.66	13.4
25	Cylinder Assy: Drag Brace Lug	40.9	40.9	40.9	40.9
Points Stressed in Tension for Forward Tow Loads:					
① 1	Pin - Drag Brace Knee	14.8	2.94	1.38	14.8
3	Pin - Trunnion, Drag Brace	53.5	13.5	6.63	53.5
8	Pin - Drag Brace, Lower	61.0	13.9	6.89	61.0
○ 28	BL-22 Diagonal $K_T = 3$	.355	2.25	.61	9.0
	BL-22 Diagonal $K_T = 3.5$	.143	1.0	.24	2.7
	BL-22 Diagonal $K_T = 4$	.072	.50	.116	1.0

① Items shown in Figure 5-3

② Design life is 200,000 flights for all items except BL-22 diagonal, which has a design life of 72,000 flights

③ See Figure 5-4

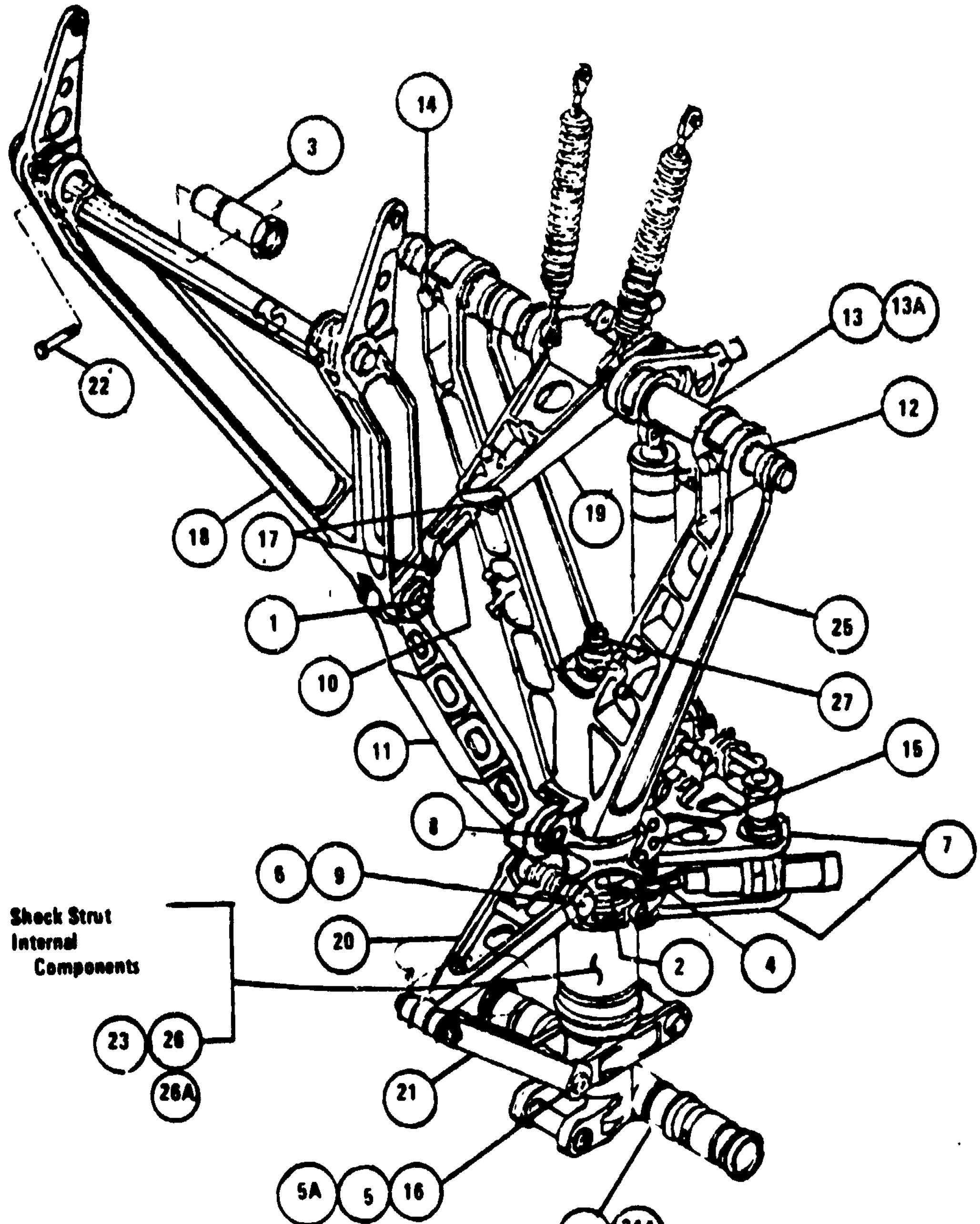

Figure 5-3. L-1011 Nose Landing Gear Part Identification

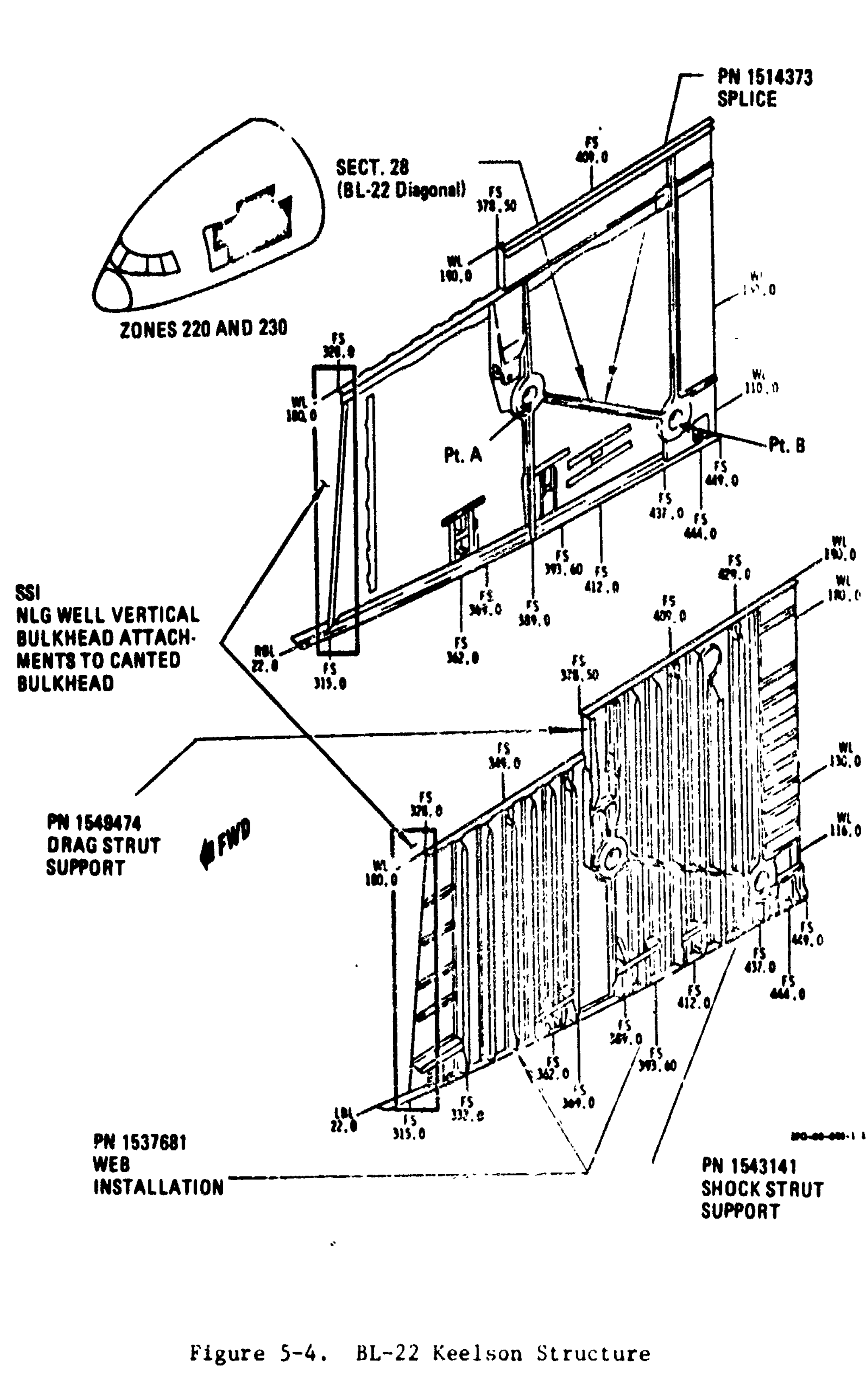

Figure 5-4. BL-22 Keelson Structure

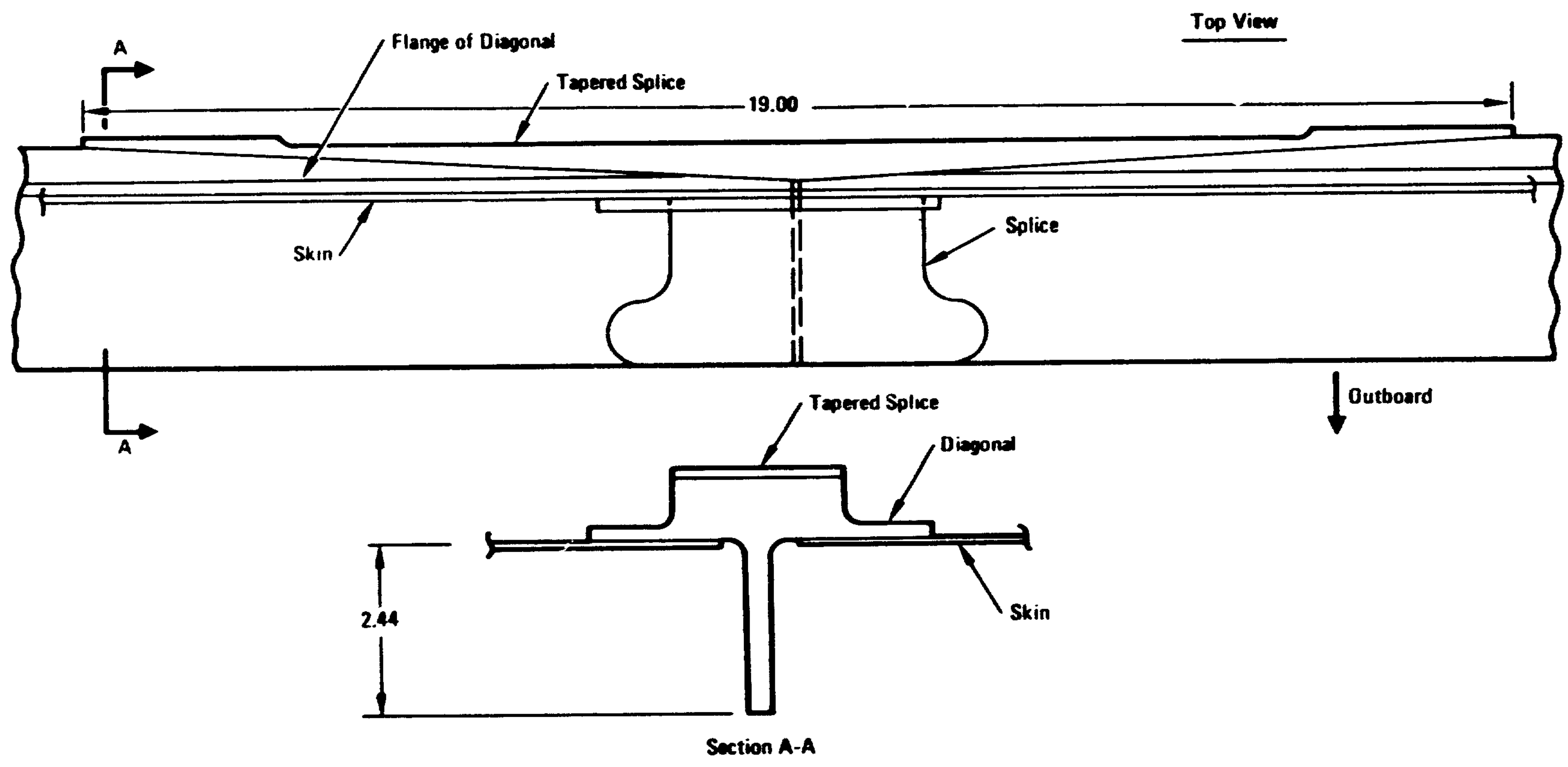

Figure 5-5. BL-22 Diagonal Joint

spectrum at 432,000 pound airplane weight is substantially less damaging to the BL-22 diagonal than is the design spectrum at 468,000 pounds, which was used as the basepoint for the current study. Since a meaningful K_{TEST} is not available for the BL-22 diagonal, Table 5-1 shows predicted fatigue lives for three assumed K_T values between 3 and 4. Experience with similar joints indicates that a K_T of around 3.5 is appropriate. For any K_T value, the extended towing spectrum is less critical than the design load spectrum. As defined previously, the term extended towing represents an operation involving towing at all airports similar to the extended towing proposed at Boston-Logan. If extended towing is only applied at Boston-Logan, then an airplane would be exposed to a mixture of "extended" and "normal" towing. The worst possible case would be an airplane that always returns to Boston-Logan, resulting in a 50 percent mix of normal and extended towing. From Table 5-1, at a K_T of 3.5, the predicted fatigue life of the BL-22 diagonal for this mix would be about 387,000 flights. The design fatigue life for this fail-safe structure is 72,000 flights. (To obtain the fatigue life for a mixture of two operations, the fatigue damage per flight is averaged and then inverted to obtain fatigue life.)

Static test results for the L-1011-3 airplane indicated that the measured stresses in the BL-22 diagonal, per unit towbar load, are about one-half of the analytically predicted values. This is apparently due to the high degree of structural redundancy in this area, which is not fully accounted for in the conservative stress analysis. The predicted fatigue lives using the test stress/load ratios are greater than 10×10^6 flights for all load spectra. The fatigue life estimates in Table 5-1 are based on the conservative stress analysis.

For points 8-1-3A and 25-8L in Table 5-1, the predicted fatigue life is the same regardless of the type of towing spectrum. For these parts, the fatigue damage is all done by ground handling conditions other than towing. For point '8-10, the upper trunnion socket, extended towing is less damaging than norma towing. The extended towing spectrum deletes two 30-foot radius turns from the total of 12 turns in the basic ground maneuvering spectrum, while the normal towing spectrum includes these turns. For the upper trunnion socket, the loading from these two turns contributes significantly to the fatigue damage, resulting in the apparent anomaly of improved fatigue life with extended towing.

Table 5-2 shows the predicted fatigue life for the BL-22 diagonal for different levels of enforcement of extended towing operations. Data are presented for three levels of enforcement; 24 hours/day, 12 hours/day at night and 1 tow/day. The effect of airplane routing is also shown at three discrete levels. This represents the fraction of operations for a specific airplane at airports enforcing extended towing. As discussed earlier, the greatest exposure to extended towing possible if only Boston-Logan enforces extended towing is the 50 percent column in Table 5-2. The 100 percent column represents extended towing enforcement at all airports utilized by a specific airplane.

The data in Table 5-2 are derived from the results in Table 5-1 for the BL-22 diagonal at a $K_T = 3.5$, using the conservative stress analysis ratio of critical stress/towbar load. Eastern Airline's schedule for the L-1011 at Boston-Logan during September 1978 was used to determine the proportion of operations between 7 PM and 7 AM, for the 12 hour/day enforcement level. The EAL Logan data indicates that 3 operations out of 10 total per day occur between 7 PM and 7 AM. Therefore, the 12 hour/day, 100 percent block in Table 5-2 was derived as a mixture of 30 percent extended towing and 70 percent normal towing. Similarly, the 1 tow/day, 100 percent block is a mixture of 10 percent extended towing and 90 percent normal towing. The data in Table 5-2 is based on the assumption that different airplanes within the fleet are rotated among the available flights, so that the same airplane is not always used for the same flight every day.

It must be re-emphasized that even for the most severe towing possible, 24 hours per day at all airports, the calculated fatigue life for the most critical part on the L-1011 is 240,000 flights, compared to a design fatigue life of 72,000 flights for this part.

TABLE 5-2. CALCULATED FATIGUE LIVES FOR VARIOUS LEVELS OF ENFORCEMENT OF EXTENDED TOWING, BL-22 DIAGONAL

Daily Enforcement of Extended Towing:	Fatigue Life (Flights) for Indicated Airplane Routing Exposure to Airports Enforcing Extended Towing		
	None	50 Percent	100 Percent
24 Hours per Day	1,000,000	387,000	240,000
12 Hours per Day (1)	1,000,000	678,000	513,000
1 Tow per Day	1,000,000	863,000	759,000

(1) Between 7 PM and 7 AM

SECTION 6

DIFFERENT TOWING CONCEPTS

6.1 DISCUSSION OF ALTERNATE TOWING CONCEPTS

A number of techniques have been proposed for the ground movement of airplanes in lieu of conventional towing. In general, the objectives of these alternative towing concepts fall into one of the following categories:

- Reduce the loads on the airplane.
- Allow more rapid towing to reduce operating costs associated with unproductive time on the ground.

The following is a list of towing systems concepts discussed in Reference 1 and in various company brochures:

1. On-board Powered Wheel System. - A high-capacity APU is used to provide hydraulic power to drive main gear wheel power units. The obvious disadvantage of such a system is the reduction in payload due to high system weight. The Boeing Company has estimated that, for a 727-type airplane, the added weight would be around 1000 pounds to provide 100 hp to the landing gear wheels, permitting a ground speed of about 10 mph.

2. Tractor Transmitting Power to Main Gear Wheels. - The tractor mates up with main gear wheels and transmits power to the wheels. Air Logistics Corporation has built such a system for use with the USAF's B-52. The design was sized for a 300,000 pound airplane weight, 5 mph ground speed and a 2.6 percent grade capability. While this system is suitable only for the B-52 with the bicycle-type landing gear, a system using adjustable trailing booms to interface with the main gears has been proposed in Reference 1. This system is illustrated in Figure 6-1. The nose landing gear is jacked up so that it rests on the aft portion of the tug; the jack is integral with the tug. An alternative design has the nose gear unloader at the front of the tow vehicle. The power transfer booms are adjustable to accommodate any large transport airplane. The booms terminate in a hinged power transfer unit

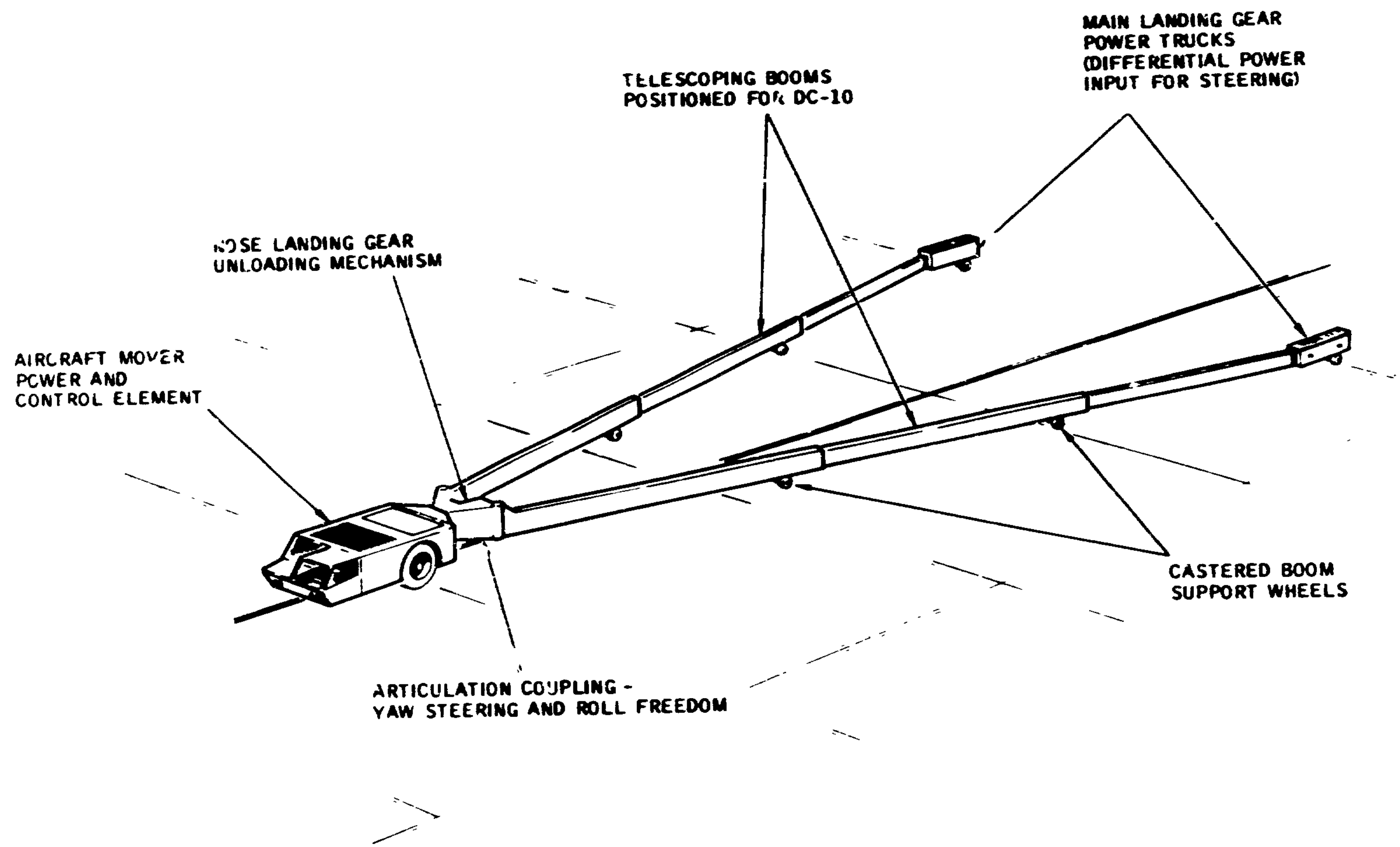

Figure 6-1. Main-Wheel-Drive Towing Concept

consisting of two electric motor/hydraulic clutch assemblies in an adjustable torque reactor member. The latter adjustment permits the clutches to be aligned and engaged with the inboard wheels on the aircraft main gear assembly. In operation, electrical power is applied to two of the wheels on each of the airplane main gears and to the tug, moving the airplane. Steering is accomplished by a combination of steering the tug and differentially powering the airplane wheels.

3. VAPS - Vehicle Auto Positioning System. - This concept developed by John W. McDonnell Associates involves the use of conventional tow tractors configured to track guidance wires implanted in taxiways, ramps and apron areas. The purpose of this system is to provide fully automated control of all airplane ground movements. Ground traffic could be under the direct control of tower personnel, possibly even fully computerized. Essentially the same concepts have been proposed by Vanley Systems under the acronym AMS for Aircraft Movement System.

   The AMS concept includes a telescoping towbar with cylinder pressure monitoring, a load cell on the tractor end of the towbar, mechanical fuse pins on the airplane end and remote cockpit control for emergency decoupling. An automatic collision avoidance system is also proposed with the AMS. The intent of these systems is to compensate for the slower speeds of the towing operation versus conventional taxiing by automating the entire ground movement process to reduce traffic delays.

4. Nose Gear Power Transfer System. - This system concept, shown in Figure 6-2, uses a towbar equipped with a pair of powered rollers driving against the airplane nose gear tires. The roller speed would have to be synchronized with the tractor forward velocity, and a method of providing power to the rollers provided. The objective is to use that portion of the airplane weight borne by the nose gear in developing tractive force, enabling the use of a lighter tow vehicle.

5. Captive Nose Gear. - The French company Secmafer S.A. has developed a tractor illustrated in Figure 6-3 in which the nose wheels ride on a turntable in the aft region of the tractor. The portion of the airplane weight borne by the nose gear is transmitted to the tractor, enabling the use of a lighter tractor. The turntable allows the tractor to turn relative to the airplane without turning the nose wheels. This feature is intended to allow the airplane steering to remain operative during the tow, so that airplane steering is immediately available after tractor/airplane separation. The ramp in the rear of the tractor is used to slide under the nose wheels during engagement. Secmafer has actually built and tested this system with the A300 and B-747.

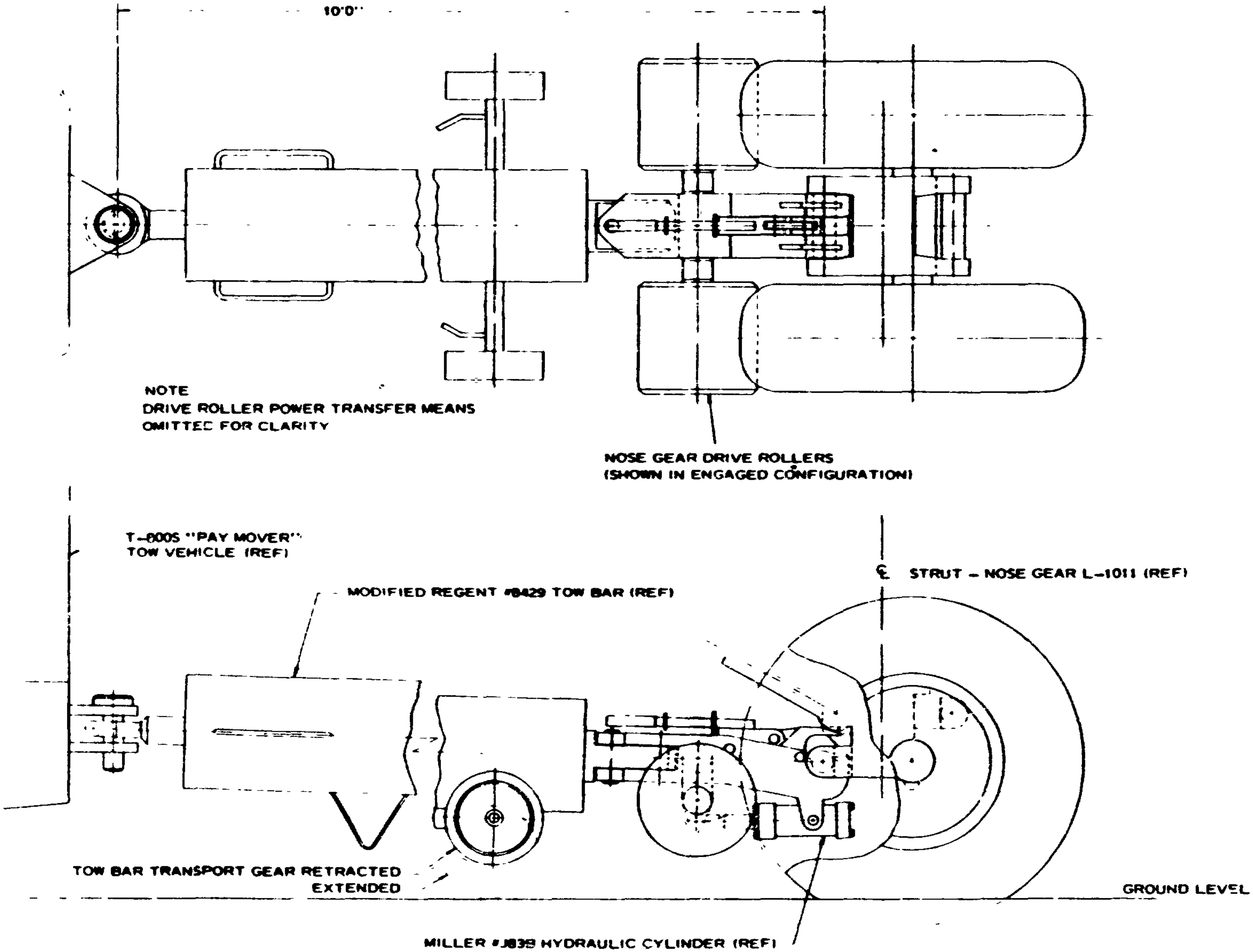

Figure 6-2. Nose Gear Power Transfer System

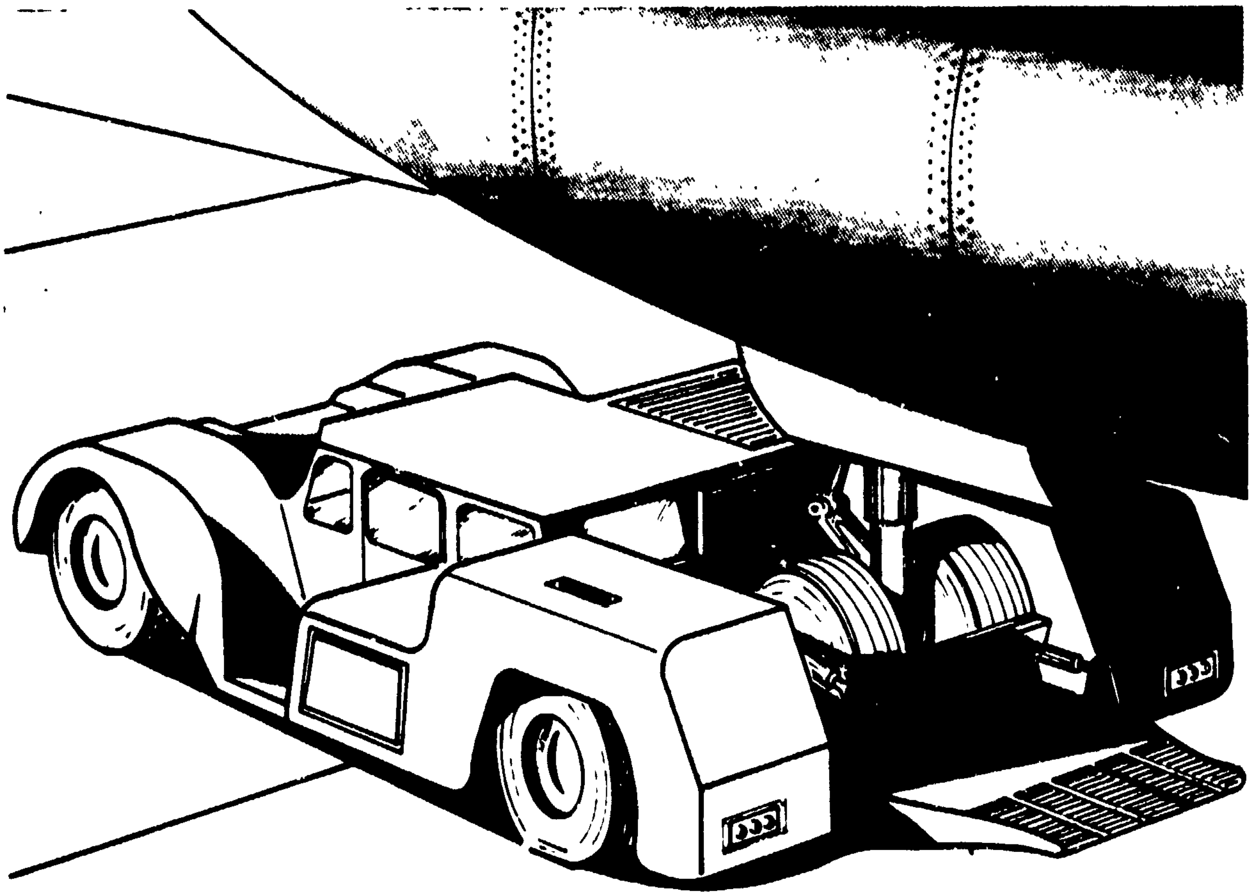

Figure 6-3. Captive Nose Gear Towing System

Systems 1 and 2 in the preceding list are the only ones that actually alleviate nose gear loads during extended towing. For these systems the main wheels are powered, providing airplane motion without loading the nose gear, but at considerable expense in terms of either added airplane weight or tow vehicle complexity. The remaining systems apply the tractive effort to the nose gear, and despite the considerable differences in design, in each case the towing load is applied at approximately axle level. The captive nose gear system has been modeled analytically with the CSMP towing program. The resulting peak nose gear loads are virtually identical to those obtained during conventional towing, with only the fore- [illegible] frequency changing somewhat due to the flexibility of the nose tires in the fore-aft load path.

Analyses have also been performed using a relocated nose gear tow point. Moving the towbar attach point up to the intersection of the upper torque arm and the steering collar, Figure 5-1, results in dynamic towbar loads that once again are virtually identical to the loads with the basic towing configuration. However, these loads are now applied higher up on the nose gear, resulting in lower loads and stresses in the drag link chain. Stress analysis of these loads, for the extended towing spectrum, shows a predicted life at the critical section of 2.7×10^6 flights, compared with 240,000 flights for the extended towing spectrum applied at the tow lug (Table 5-1). However, the steering collar was never designed to take direct towing loads, so that undoubtedly considerable redesign would be required to accept these loads. Additionally, the problem of designing both a towbar and steering collar for convenient hookup is a formidable one.

6.2 COST IMPACT OF EXTENDED TOWING OPERATIONS

Since the predicted loads from extended towing at Boston-Logan present no fatigue problems for the L-1011, there is no reason to change to an alternate towing system for the purpose of reducing nose gear loads. However, there may be an incentive to use a system allowing higher towing speeds, to reduce the operating costs associated with airplane movement time on the ground. To quantify this potential problem, an estimate of the cost of extended towing at Boston-Logan was made. Table 6-1 shows the operating times used in the analysis. Separate times were calculated for operation of the airplane engines, APU, tug and airplane crew time. The cost comparisons pertain only to the region of Boston-Logan shown in Figure 6-4 involving potential extended towing. The following assumptions were made in the analysis:

- During forward taxi, the airplane accelerates at 0.2g up to 15 mph and then maintains a constant velocity.
- During forward towing, the airplane/tug combination accelerates at 0.025g up to 7 mph, and then maintains a constant velocity.

TABLE 6-1. OPERATING TIME ESTIMATES, EXTENDED TOWING AT BOSTON-LOGAN

Operation	Operating Time (Minutes) For:			
	A/P Engines	APU	Tug	A/P Crew
Conventional Taxiing				
Departure:				
Pushback	3.6	-	3.6	3.6
Forward Taxi	1.2	-	-	1.2
Tug Return	-	-	1.8	-
TOTAL	4.8		5.4	4.8
Arrival:				
Forward Taxi	0.9	-	-	0.9
TOTAL	0.9	-	-	0.9
Extended Towing				
Departure:				
Pushback	-	3.6	3.6	3.6
Forward Tow	-	2.3	2.3	2.3
Tug Return	-	-	2.5	-
TOTAL	-	5.9	8.4	5.9
Arrival:				
Tug Deployment	-	-	3.0	3.0
Hook-Up	-	-	1.0	1.0
Forward Tow	-	-	2.2	2.2
TOTAL	-	-	6.2	6.2
Overall Totals				
Conventional Taxiing	5.7	-	5.4	5.7
Extended Towing	-	5.9	14.6	12.1
Difference/2	-2.85	2.95	4.6	3.2

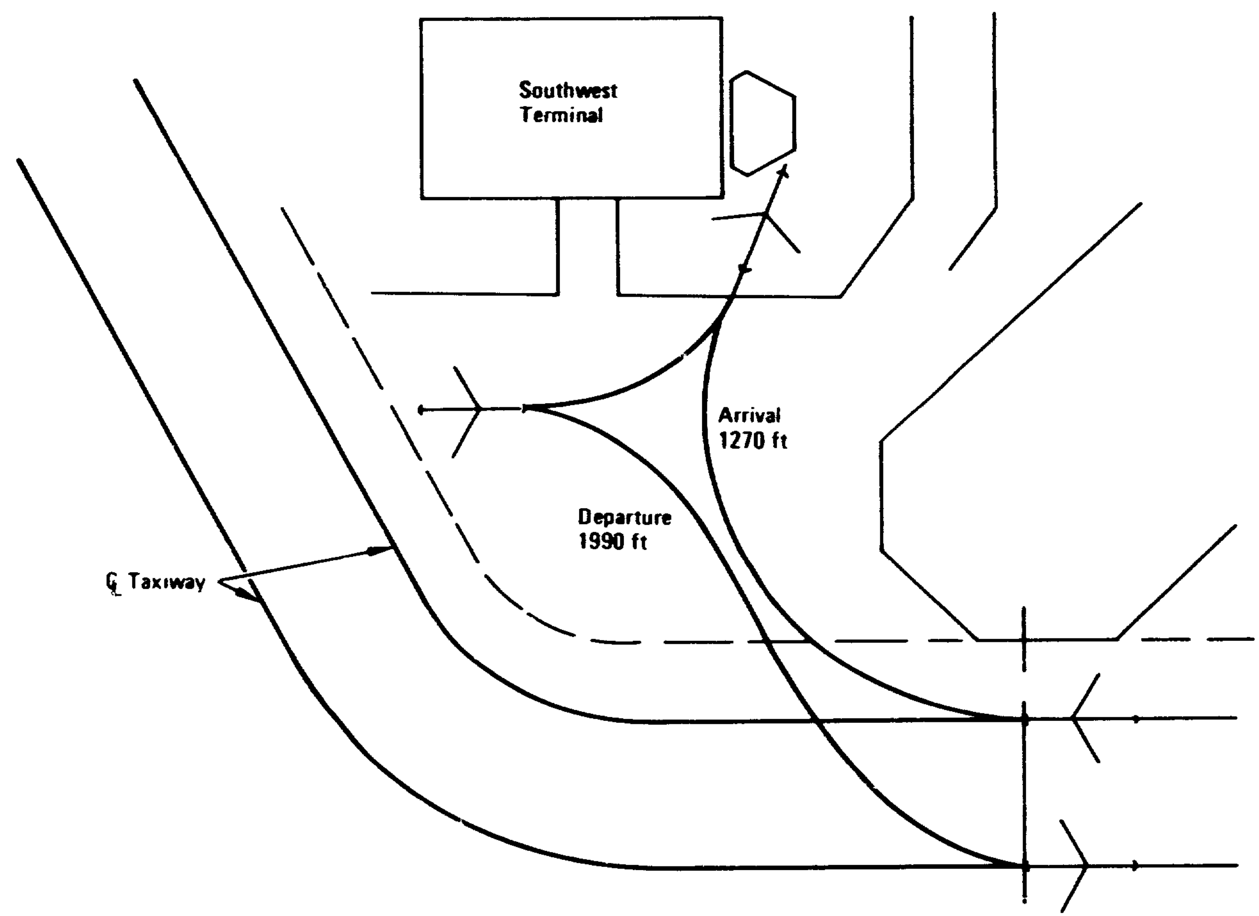

Figure 6-4. Towing Paths, Southwest Terminal Region, Boston-Logan Airport

- During the taxi arrival, a constant velocity of 20 mph is maintained through the right turn, yielding about 0.05 g lateral acceleration. The airplane decelerates at 0.2 g to a stop at the gate.

- With extended towing, the tug deployment time on arrival occurs while the airplane is waiting to be towed. The tug is not in place ready for hook-up when the airplane arrives at the hook-up point.

At the bottom of Table 6-1 are shown the total times for both conventional taxiing and extended towing. The differences between these represent the time differentials for two flights (minimum), since the airplane must fly to another destination and return before accumulating the time differences shown. Therefore, Table 6-1 also shows the time differences divided by two, which are appropriate for a per flight analysis.

Table 6-2 shows a comparison of the costs of conventional taxiing and extended towing. The fuel and crew costs and fuel consumption rates used are also shown in Table 6-2. All costs represent summer 1979 average levels for the L-1011. Crew costs are taken from Reference 3, updated to mid-year 1979 assuming a 12 percent annual inflation rate. The bottom line in Table 6-2 shows that the added crew costs during extended towing override the fuel cost savings, resulting in a net cost penalty of $11.12 per flight. If it is assumed that upon arrival the tug is waiting at the hookup point, the reduced airplane crew costs associated with waiting for the tug reduce the cost penalty for extended towing from $11.12 per flight to a savings of $1.80 per flight. On the other hand, if the airplane taxing velocity were assumed to be 30 mph during both departure and arrival, the cost penalty would increase from $11.12 to $17.84 per flight. These examples illustrate that the cost tradeoff results are quite sensitive to the operating time estimates.

Table 6-3 presents the cost penalty data as a function of different levels of enforcement of extended towing and different airplane routing exposure to airports enforcing extended towing. The $11.12 figure from Table 6-2 represents 24-hour/day enforcement at Boston-Logan, and an airplane routing in which every flight is to or from Boston-Logan. The 12 hours/day and 1 tow/day costs are derived using the same methods discussed in Section 5 for Table 5-2. The numbers in the center column represent the maximum cost penalty incurred if only Boston-Logan used extended towing.

TABLE 6-2. OPERATING COST ESTIMATES, EXTENDED TOWING AT BOSTON-LOGAN

	A/P Engines	APU	Tug	A/P Crew	Total Costs
Consumption Rate, gpm	11.0	1.1	0.1	-	
Fuel Cost, $/gal	0.60	0.60	0.90	-	
Crew Cost, $/min	-	-	0.20	8.33	
Operating Cost, $/Min	6.60	0.66	0.29	8.33	
Total Costs					
Conventional Taxiing, $/Flight	37.62	-	1.57	47.48	86.67
100% Extended Towing, $/Flight	-	3.89	4.23	100.79	108.91
Difference/2 = Cost Penalty Per Flight	-18.81	1.95	1.33	26.65	11.12

TABLE 6-3. ESTIMATED COST PENALTIES FOR VARIOUS LEVELS OF ENFORCEMENT OF EXTENDED TOWING

Daily Enforcement of Extended Towing	Cost Penalty ($/Flight) for Indicated Airplane Routing Exposure to Airports Enforcing Extended Towing		
	None	50 Percent	100 Percent
24 Hours Per Day	0	11.12	22.24
12 Hours Per Day	0	3.34	6.68
1 Tow Per Day	0	1.11	2.22

The right-hand column in Table 6-3 represents the cost penalty if all airports, used by a given airplane, enforced extended towing with the same time delays shown in Table 6-1. Since the data in Table 6-1 are peculiar to Boston-Logan only, using the paths shown in Figure 6-4, the right-hand column in Table 6-3 is only a rough estimate of the impact of extended towing beyond Boston-Logan. Since extended towing at other airports could readily involve much greater distances than those required at Boston-Logan, the cost penalties at other airports could be substantially greater than at Boston-Logan. Estimating these penalties is beyond the scope of the present contract. However, as an illustration, if the forward towing distances at Boston-Logan were doubled, the cost penalty would more than double, from $11.12 per flight to $28.90 per flight.

Reference 1 also presents estimated annualized hardware acquisition costs for alternate towing concepts, based on towing operations at LAX. Converting those to cost per flight and updating the data to account for inflation from 1973 to 1979 (using the Consumer Price Index), the acquisition costs for alternate towing systems would average about $9 per flight. While this is slightly less than the estimated cost penalty for extended towing of $11.12 per flight, a number of factors tend to discourage the investment in alternate towing concepts or hardware, including the following:

- The cost penalty of $11.12 per flight is applicable only to an airplane which departs from or arrives at Boston-Logan every flight.
- Even this cost penalty can be reversed to a small cost savings ($1.80 per flight) merely by scheduling tow vehicle traffic to meet arriving airplanes at the hookup point.
- Based on recent experience, fuel costs can be expected to increase more rapidly than crew costs. This would reduce the cost penalty (in constant 1979 dollars) by giving greater weight to the fuel savings with extended towing. As an example, if fuel costs double in the same time that crew costs increase 50 percent, the cost penalty reduces to $5.94 per flight, in constant 1979 dollars.

Reference 4 is a study of the time delay and excess fuel consumption associated with terminal area air traffic. The time delays are the results of routing arriving traffic in holding patterns or using path-stretching and speed control to accommodate heavy traffic. The time delay and fuel consumption data from Reference 4 are based on recorded operations at Chicago O'Hare (ORD) during 1974-75. The average delay time due to traffic conditions is 10 minutes, and the average excess fuel consumption is 157 gallons. For the L-1011, the average excess fuel consumption would be around 300 gallons. Using current fuel and crew costs, the cost of a 10-minute delay is about $263 per flight for the L-1011.

While these results at ORD (noted for its heavy traffic) have no direct bearing on the effects of extended towing at Boston-Logan, the results are shown to help place the estimated towing cost penalties in proper perspective. It seems clear that a cost penalty of up to 11 dollars per flight for extended towing is insignificant compared with the cost penalties associated with airborne time delays. (The Reference 4 data apply only to the arrival phase; no estimates are given for departure delays due to traffic.)

Based on the results of Sections 5 and 6, it is concluded that there is not sufficient justification for investing in alternative towing equipment, either to reduce nose gear towing loads or the costs of extended towing at Boston-Logan.

SECTION 7

LIMITING CONDITIONS

The acceptability of extended towing operations at Boston-Logan is contingent upon certain limiting conditions co guarantee that the nose gear towing loads do not cause unacceptable fatigue damage, and that the safety of the towing operation is commensurate with conventional powered taxiing.

The factors which influence the acceptability of the nose gear towing loads during extended towing at Boston-Logan include the following:

- Airplane Gross Weight - The fatigue life results in Section 5 are based on an airplane gross weight of 468,000 pounds. For the BL-22 diagonal, using calculated stress values (which are conservative compared to test results), the extended towing spectrum and a K_T of 3.5, the estimated fatigue life equals the design life (72,000 flights) at an airplane gross weight of 550,000 pounds. This assumes that the towing loads are proportional to airplane weight which, from the analytical results in Section 3, is true only if the tug driver tries to maintain a constant acceleration history, regardless of airplane weight. For a fixed throttle input history, the towing loads increase with airplane weight at a rate less than proportional to airplane weight. The 550,000 pound limit applies to extended towing at all airports; for extended towing only at Boston-Logan the limiting weight is 569,000 pounds.

- Number of Start/Stop Cycles per Flight - The predicted fatigue lives for extended towing are based on a rate of five start/stop cycles per flight. This allows for two cycles during departure, one during arrival, one for maintenance and one due to traffic delays. The BL-22 diagonal would not become critical (at 468,000 pounds) until a rate of 17 start/stop cycles per flight were achieved, using calculated stress values. A cyclic rate this high would be very difficult to achieve at Boston-Logan with the currently proposed distances for extended towing. The following factors could lead to an increase in the assumed rate of start/stop cycles.

    - Longer towing distances, particularly into regions of heavy traffic.

- Unusually frequent maintenance towing, particularly coupled with long tows in heavy traffic.

- Inexperienced tug operator or ground crew.

- Driver Technique - Towing loads are very sensitive to driver technique. With the L-1011 at normal operating weights, the steady towing load is less than 10,000 pounds, and the dynamic peaks with an experienced tug operator are normally below 15,000 pounds. The highest load observed during testing (and included in the fatigue load spectrum developed in Section 4) is 36,000 pounds tension which occurred during the Palmdale tests with an inexperienced tug driver. The next highest load is 28,000 pounds tension, occurring at LAX with an experienced driver who was in a hurry to tow an arriving airplane. Deliberate attempts to achieve high loads with abrupt starts and stops during the Palmdale testing achieved towbar loads of around 33,000 pounds (both tension and compression). Therefore, the towing load spectrum used to represent the proposed extended towing at Boston-Logan already includes loads that exceed the levels that were attained when the tug driver was deliberately trying to develop high loads.

  For the BL-22 diagonal, an increase in the towing loads of 18 percent (peak load = 42,300 pounds) would be required to reduce the fatigue life for all-airport extended towing from 240,000 flights to the design life of 72,000 flights, based on calculated stress values and a K_T = 3.5. For Boston-Logan-only extended towing, a load increase of 27 percent (peak load = 45,900) would be required.

- Tow Vehicle Transmission Characteristics - The test results are obtained with International Harvester-Hough Model T-300S, T-500S and T-800S tractors. With the T-500S and T-800S tugs, significant dynamic loads (>25,000 pounds) have been observed during shifting from second to third gear. This factor is also related to driver technique; rough shifts appear to occur only at full throttle. From the analytical results of Section 3, it is clear that the time-delay of tug thrust buildup, due to the slippage in the automatic transmission, is essential to reduce the potential peak towing loads during initial startup. Tow-bar axial loads as high as 80,000 pounds are theoretically possible with a step input of the maximum available tug thrust at zero velocity, using the T-500S tug. Tow vehicles with transmission characteristics different from the Hough tractors could lead to significantly increased dynamic towing loads.

Of the above factors, only the airplane weight is readily monitored and controlled. A logical limiting condition for extended towing at Boston-Logan would involve the specification of a maximum allowable takeoff gross weight for extended towing. However, for the L-1011 this limit is well above any currently projected maximum airplane gross weight, even using conservative calculated stresses for the most critical structure.

Also of concern are the factors that affect the safety of the extended towing operation compared to conventional taxiing. These factors are primarily towing velocity and surface conditions. No attempt was made during this program to define a maximum speed for safe control of the tug/airplane combination. The highest velocities observed during the test program are:

- LAX - 9 mph
- Palmdale - 12 mph
- Dorval - 9 mph

At LAX and Dorval, the 9 mph speeds occurred during long tows between the terminal and maintenance hangars, with lightweight airplanes. At Palmdale, the 12 mph run was performed with a heavy airplane (376,000 pounds) and a small single-engine tug (T-180) on a slight downhill slope. The tug experienced some difficulty stopping, with airplane braking used to assist the stop for the last few seconds. There were no difficulties with directional control during this run and stop. At LAX and Montreal, the long 9 mph tows were performed with the T-500S tug, which was designed for the L-1011. At Montreal, the high-speed portions of the tow were performed both on dry runways and with 3-4 inches of compact snow and ice. Chains were used on the tug at Montreal at all times, regardless of surface conditions. There was never any indication of directional control or stopping difficulties at either LAX or Montreal.

Based on the test results, it appears that a speed limit during extended towing at Boston-Logan could be specified on the order of 12 mph for dry conditions and 9 mph for rain or snow/ice conditions. These limits would apply only for a tug sized for the L-1011, such as the T-500S or T-800S or their equivalent. Smaller tugs should have a lower speed limit. A further restriction would be the requirement to use chains on the tug during snow/ice conditions. It would also seem prudent to use only experienced tug drivers for the operational extended towing at Boston-Logan, particularly during adverse weather conditions. The suggested speed limits are close to the maximum speed capability of the T-500S tug towing a heavyweight L-1011 on a level surface, and are well above the maximum towing speed (7 mph) used in the cost analyses discussed in Section 6.2.

SECTION 8

CONCLUSIONS

The following conclusions are derived as a result of the current study:

- The proposed extended towing at Boston-Logan Airport does not reduce the predicted fatigue life of the L-1011 nose gear and supporting structure to below the design fatigue life.

- The proposed extended towing at Boston-Logan Airport, using existing towing equipment, results in a slight cost penalty (11 $/flight) due to the longer time on the ground during towing compared to powered taxiing. The crew costs during the time delay are greater than the fuel cost savings from having the airplane engines shut down during towing.

- Dynamic towing loads are very sensitive to tug driver technique. Peak dynamic loads three times as large as typical dynamic loads were observed during the testing. These measured loads are considered typical of experienced tug driver practices, and are included in the extended towing load spectrum. Deviations from accepted towing procedures can result in dynamic loads of sufficient magnitude to reduce the fatigue life of the nose gear.

- Dynamic towing loads are also sensitive to tow vehicle transmission characteristics, particularly during gear shifting.

- No unusually high towing loads were measured during testing at Dorval, Montreal with ice and snow covered taxiway surfaces. No difficulties were encountered in controlling the tug/airplane combination under these conditions.

- Dynamic towing loads large enough to be significant from a fatigue damage viewpoint normally occur only at the start and stop of a towing operation. The only exception to this is the occasional occurrence of large dynamic loads during tug gear shifts.

REFERENCES

1. Forsyth, R. W., et al: Systems for Transporting Aircraft on the Ground. FAA-RD-74-92, 1974.

2. Wollard Aircraft Equipment, Inc.: Operation, Maintenance and Repair Manual with Illustrated Parts Catalog for Aircraft Towbar Models TB-571 and TB-571-C. 71-0623, TB-571, 1978.

3. Anon: Operating and Cost Data, 747, A300B, DC-10 and L-1011 - First Quarter, 1979. Aviation Week and Space Technology, July 2, 1979.

4. Halverson, A. G. and Jolitz, G.: Terminal Area Delay and Fuel Consumption Analysis. FAA-EM-78-20, 1979.

APPENDIX A

CSMP TOWING LOADS PROGRAM LISTING

Figure A-1 is a listing of the CSMP program used for analytically determining dynamic towing loads. The analytical model is described in Section 3.1. The input and output data are described in Tables A-1 and A-2, respectively. All quantities are in inch, pound, radian and second units unless otherwise noted.

****INTERACTIVE CONTINUOUS SYSTEM MODELING PROGRAM - ICSMP****

PROBLEM INPUT STATEMENTS

```
TITLE  RUN 200  08-10-79
TIMER  FINTIM= 4.,  OUTDEL=.010 , PRDEL=.2 ,  DELT=.001
PARAM XDOTIC=0. , V0=1.
PARAM W=382000.  ,I=1.8E8   ,CG=.258 ,LEMAC=1143. ,CBAR=293.52
PARAM WM=10572.,  WN=586.
PARAM FSM=1280.,FSN=440.,WLM=158.5,WLN=116.,WLCG=190.
PARAM LOM=144.6, LON=98.56,RM=24.9, RN=18.275
PARAM KTM=96000., KTN=16000.,BTM=362.,BTN=36.
PARAM FAOM=84308., FAON=7390., FAAM=2850., FAAN=416.
PARAM BMT=520. , BMC=13.2 , BNT=69.4 , BNC=16.
PARAM EM=28.642 , EN=18.93 , ZETNOS=.1
PARAM W15=110000. , I15=1.6E6 , HCG05=36.72
PARAM W18=108000. , I18=2.1E6 , HCG08=37.43
PARAM DXF5=71. , DXR5=71. , DXCH05=168. , DZCH5=18.
PARAM DXF8=82. , DXR8=82. , DXCH08=187. , DZCH8=16.
PARAM BCH=279.
PARAM KTF5=20200. , KTR5=20200. , BTF5=74. , BTR5=74.
PARAM KTF8=15727. , KTR8=15727. , BTF8=59.3, BTR8=59.3
PARAM LTB=120. , DS5=0.405 ,  DS8=0.405
PARAM MUM0=.015, MUN0=.015, MUMV=0. , MUNV=0.
PARAM MUTOW0=.015, MUTOWV=0.
PARAM KIP=1000. , FL1=0. , FL2=0. , FL3=0. , FL4=0.
PARAM FL500=1.  , FWDREV=1. , FL800=0.
*  FWDREV=1. FOR PULLING, -1. FOR PUSHING
PARAM FLBRAP=0. , FLBRTV=0.
PARAM SLOPE=0.
PARAM MODE= 1., VFINAL=3.5  ,TC=3.  , TD=3.
PARAM TUG=5.  ,  KHITCH=1.0E6 , BHITCH=1477.
*  TUG=5 FOR T-500S, TUG=8 FOR T-800S
MACRO ZHT,ZHTD=RUNWAY(XX,XXD)
XRW=XX-XSTART
HT=SLOPE*XRW
ZHT=INSW(XRW,0,HT)
ZSL=INSW(XRW,0,SLOPE)
ZHTD=ZSL*XXD
ENDMAC
INIT
X1D0=XDOTIC
XND0=XDOTIC
XMD0=XDOTIC
X2D0=XDOTIC
Z1D0=0.
ZND0=0.
ZMD0=0.
Z2D0=0.
THD0=0.
TH1D0=0.
TH0=0.
TH10=0.
DELN0=0.
G=386.
CONV=5./88.
FSCG=LEMAC+CG*CBAR
DXM=FSM-FSCG
```

Figure A-1. CSMP Towing Program Listing (Sheet 1 of 6)

```
DXN=FSCG-FSN
DZM=WLCG-WLM
DZN=WLCG-WLN
FZGN=W/(1+DXN/DXM)
FZGM=W-FZGN
FZTM=FZGM+WM
FZTN=FZGN+WN
FZTF=W1/(1+DXF/DXR)
FZTR=W1-FZTF
ZF=FZTF/KTF-HCG0
ZR=FZTR/KTR-HCG0
Z10=(ZF+ZR)/2.
ZCH=Z10+DZCH
ZN0=FZTN/KTN-RN
ZM0=FZTM/KTM-RM
ZTB=ZN0-ZCH
XTB=SQRT(LTB*LTB-ZTB*ZTB)
YM0=EM*(1-FAOM/(FZGM+FAAM))
YN0=EN*(1-FAON/(FZGN+FAAN))
Z20=ZM0-LOM-DZM+YM0
XM0=0.
X20=DXM
XN0=X20+DXN
XCH=XN0+XTB
X10=XCH+DXCH0
XSTART=X10+DXF
A=VFINAL/CONV/G/(TC+TD)*FWDREV
PI=3.1415926535
*  TUG PARAMETERS
STUG=TUG-7.
W1     =INSW(STUG,W15   ,W18    )
I1     =INSW(STUG,I15   ,I18    )
HCG0   =INSW(STUG,HCG05 ,HCG08  )
DXF    =INSW(STUG,DXF5  ,DXF8   )
DXR    =INSW(STUG,DXR5  ,DXR8   )
DXCH0  =INSW(STUG,DXCH05,DXCH08)
DZCH   =INSW(STUG,DZCH5 ,DZCH8  )
KTF    =INSW(STUG,KTF5  ,KTF8   )
KTR    =INSW(STUG,KTR5  ,KTR8   )
BTF    =INSW(STUG,BTF5  ,BTF8   )
BTR    =INSW(STUG,BTR5  ,BTR8   )
DS     =INSW(STUG,DS5   ,DS8    )
*  KINEMATICS
DYNAM
METHOD RKSFX
STH1=SIN(TH1)
CTH1=COS(TH1)
STH=SIN(TH)
CTH=COS(TH)
ALPHA=ATAN(ZTB/XTB)
CATH1=COS(ALPHA-TH1)
XLF=X1+DXF
XLR=X1-DXR
ZRF,ZRFD=RUNWAY(XLF,X1D)
ZRR,ZRRD=RUNWAY(XLR,X1D)
ZRN,ZRND=RUNWAY(XN,XND)
ZRM,ZRMD=RUNWAY(XM,XMD)
ZTF=Z1-DXF*STH1+ZRF+HCG0
ZTR=Z1+DXR*STH1+ZRR+HCG0
ZTFD=Z1D-DXF*CTH1*TH1D+ZRFD
```

Figure A-1. CSMP Towing Program Listing (Sheet 2 of 6)

```
ZTRD=Z1D-DXR*CTH1*TH1D+ZRPD
HCG=HCG0-(ZTF+ZTR)/2.
X1N= (X1-XN)*CTH1+(ZN-Z1)*STH1
Z1N=-(X1-XN)*STH1+(ZN-Z1)*CTH1
ZTBP=Z1N-DZCH
XTBP=SQRT(LTB*LTB-ZTBP*ZTBP)
DXCH=X1N-XTBP
DELCH=DXCH-DXCH0
DCH=DEADSP(-DS,DS,DELCH)
DCHABS=ABS(DCH)
CL=DS-ABS(DELCH-DCH)
XCH=X1+DZCH*STH1-DXCH*CTH1
ZCH=Z1+DXCH*STH1+DZCH*CTH1
XTB=XCH-XN
ZTB=ZN-ZCH
VTOW=(X1D*CTH1-Z1D*STH1)*CONV
VTOWFR=FWDREV*VTOW
VTREL=VTOW/CONV/V0
VTLIM=LIMIT(-1.,1.,VTREL)
DELCHD=X1ND-XTBPD
XTBPD=-ZTBP*Z1ND/XTBP
X1ND =  (X1D-XND)*CTH1 + (ZND-Z1D)*STH1...
      -((X1 -XN )*STH1 - (ZN -Z1 )*CTH1)*TH1D
Z1ND = -(X1D-XND)*STH1 + (ZND-Z1D)*CTH1...
      -((X1 -XN )*CTH1 + (ZN -Z1 )*STH1)*TH1D
ZTN=ZN+ZRN+RN
ZTM=ZM+ZRM+RM
ZTND=ZND+ZRND
ZTMD=ZMD+ZRMD
VXN=XND*CTH-ZND*STH
VXM=X2D*CTH-Z2D*STH
VXNREL=VXN/V0
VXMREL=VXM/V0
VXNLIM=LIMIT(-1.,1.,VXNREL)
VXMLIM=LIMIT(-1.,1.,VXMREL)
VN=(Z2D-ZND)*CTH+(X2D-XND)*STH-DXN*THD
VM=(Z2D-ZND)*CTH+DXM*THD
YN=INTGRL(YN0,VN)
YM=INTGRL(YM0,VM)
DELND=(X2D-XND)*CTH-(Z2D-ZND)*STH+DZN*THD
DELN=INTGRL(DELN0,DELND)
LN=L0N-YN
LM=L0M-YM
VXAP=(X2D*CTH-Z2D*STH)*CONV
*  FORCES
FZTF=KTF*ZTF+BTF*ZTFD
FZTR=KTR*ZTR+BTR*ZTRD
MUBRTV=FLBRTV*AFGEN(TVBR,TIME)
MUTOW=(MUTCW0+MUTOWV*VTOW*VTOW)*VTLIM
FXDR=(FZTF+FZTR)*(MUTOW+MUBRTV)
THRUST=FL1*AFGEN(T1,VTOWFR)+FL2*AFGEN(T2,VTOWFR)...
      +FL3*AFGEN(T3,VTOWFR)+FL4*AFGEN(T4,VTOWFR)...
      +FL500*AFGEN(T500,VTOWFR)+FL800*AFGEN(T800,VTOWFR)
TP=AFGEN(THR,TIME)
FXENGB=TP*FWDREV*KIP*THRUST
FXT=FXENG-FXDR
FCHABS=KIP*AFGEN(HITCH,DCHABS)
TERMM=INSW(DCH,-1.,1.)
FCH=FCHABS*TERMM
FCHD=FCH/DELCHD
```

Figure A-1. CSMP Towing Program Listing (Sheet 3 of 6)

```
FTBCH=(FCH+FCHD)/CATH1
FH=KHITCH*DCH+BHITCH*DELCHD
FTBH=FH/CATH1
FTB=INSW(STUG,FTBCH,FTBH)
FXTB=FTB*XTB/LTB
FZTB=FTB*ZTB/LTB
FZTN=KTN*ZTN+BTN*ZTND
FZTM=KTM*ZTM+BTM*ZTMD
MUTN=(MUN0+MUNV*VXN*VXN)*VXNLIM
MUTM=(MUM0+MUMV*VXM*VXM)*VXMLIM
MUBRAP=FLBRAP*AFGEN(APBR,TIME)
FXTN=MUTN*FZTN
FXTM=(MUTM+MUBRAP)*FZTM
FAN=FAON*EN/(EN-YN)-FAAN
FAM=FAOM*EM/(EM-YM)-FAAM
BHN=INSW(VN,BNT,BNC)
BHM=INSW(VM,BMT,BMC)
FHN=BHN*VN*ABS(VN)
FHM=BHM*VM*ABS(VM)
FZGN=FAN+FHN
FZGM=FAM+FHM
KXN=AFGEN(KXNOSE,YN)
BXN=ZETNOS*2.*SQRT(KXN*WN/G)
FXGN=KX' *DELN+BXN*DELND
FXGM=FXTM
MYN=-LN*FXGN
MYM=-LM*FXGM
TTC=TIME-TC
TTD=TIME-TC-TD
TMTF=TIME-2*TC-TD
TDUM1=INSW(TTC,-1.,0.)
TDUM2=INSW(TTD,0.,1.)
TDUM=INSW(TTC,TDUM1,TDUM2)
ACC1 = A*(1.-COS(PI*TIME/TC))/2.
ACC2 = A*(1.-COS(PI*(TIME-TD)/TC))/2.
ACC=FCNSW(TDUM,ACC1,A,ACC2)
ACCEL=INSW(TMTF,ACC,0.)
DRAG=FXDR+FXTM+FXTN
THRREQ=DRAG+ACCEL*(W+W1)
STUF1=AFGEN(T500,VTOWFR)
STUF2=AFGEN(T800,VTOWFR)
STUFF=INSW(STUG,STUF1,STUF2)
THRMAX=FHDREV*KIP*STUFF
TFREQ=THRREQ/THRMAX
FXENG=INSW(MODE,THRREQ,FXENGB)
*   ACCELERATIONS
X1DD=(FXT*CTH1-(FZTF+FZTR)*STH1-FXTB)*G/W1
Z1DD=(W1+FZTB-FXT*STH1-(FZTF+FZTR)*CTH1)*G/W1
TERM1=FXT*HCG+FZTF*DXF-FZTR*DXR
TERM2=(FZTB*CTH1-FXTB*STH1)*DXCH
TERM3=(FZTB*STH1+FXTB*CTH1)*DZCH
TH1DD=(TERM1+TERM2-TERM3)/I1
XNDD=(FXTB+(FXGN-FXTN)*CTH+(FZGN-FZTN)*STH)*G/WN
XMDD=X2DD
ZNDD=(-FZTB+WN+(FZGN-FZTN)*CTH-(FXGN-FXTN)*STH)*G/WN
ZMDD=(WM+(FZGM-FZTM)*CTH)*G/WM
X2DD=-((FXGN+FXGM)*CTH+(FZGN+FZGM)*STH)*G/W
Z2DD= (W+(FXGN+FXGM)*STH-(FZGN+FZGM)*CTH)*G/W
THDD=(MYM+MYN+FZGN*DXN FZGM*DXM-FXGN*DZN-FXGM*DZM)/I
*   INTEGRALS
```

Figure A-1. CSMP Towing Program Listing (Sheet 4 of 6)

```
     X1D=INTGRL(X1D0,X1DD)
     Z1D=INTGRL(Z1D0,Z1DD)
     TH1D=INTGRL(TH1D0,TH1DD)
     XND=INTGRL(XND0,XNDD)
     ZND=INTGRL(ZND0,ZNDD)
     ZMD=INTGRL(ZMD0,ZMDD)
     XMD=INTGRL(XMD0,X2DD)
     X2D=INTGRL(X2D0,X2DD)
     Z2D=INTGRL(Z2D0,Z2DD)
     THD=INTGRL(THD0,THDD)
     X1=INTGRL(X10,X1D)
     Z1=INTGRL(Z10,Z1D)
     XN=INTGRL(XN0,XND)
     ZN=INTGRL(ZN0,ZND)
     ZM=INTGRL(ZM0,ZMD)
     XM=INTGRL(XM0,XMD)
     X2=INTGRL(X20,X2D)
     Z2=INTGRL(Z20,Z2D)
     TH=INTGRL(TH0,THD)
     TH1=INTGRL(TH10,TH1D)
     *  TABLES
     AFGEN APBR=0.,0.,100.,0.
     AFGEN TVBR=0.,0.,100.,0.
     AFGEN THR= 0.,0.,.0001,1.,100.,1.
     AFGEN KXNOSE=0.,13228.,6.,18471.,14.2,29674.,18.,39683.
     AFGEN HITCH=0.,0.,.02,.6,.2,1.6,.6,4.5,1.,8.7,1.4,14.5,1.6,18.5,...
                 1.8,23.7,1.94,30.,2.,34.5,2.06,40.,2.14,50.,4.14,300.
     AFGEN T1=-100.,58.,0.,58.,1.,50.,2.,39.5,3.,22.5,3.5,0.,100.,0.
     AFGEN T2=-100.,32.,0.,32.,2.,27.,4.,18.5,5.,13.,6.,4.5,6.4,0.,100.,0.
     AFGEN T3=-100.,18.,0.,18.,6.,12.2,9.,9.8,11.,7.,11.4,5.5,12.,0.,100.,0.
     AFGEN T4=-10.,10.,0.,10.,15.,4.5,15.4,6.5,18.,6.,19.5,4.6,21.2,0.,...
              100.,0.
     AFGEN T500=-100.,59.,0.,59.,1.5,45.4,2.7,29.,3.64,24.,3.71,20.2,5.22,...
                17.1,5.3,14.4,5.5,13.7,7.38,11.5,7.41,10.,10.32,8.4,10.59,...
                6.9,13.,6.5,14.6,5.8,14.95,4.55,20.6,4.1,21.2,0.,100.,0.
     AFGEN T800=-100.,83.,0.,83.,0.4,79.,1.55,62.,1.99,56.5,2.22,...
                 50.8,3.95,31.4,6.,23.,7.4,15.,9.25,13.7,14.,10.,...
                 15.8,7.5,18.3,0.,20.,0.
     *  OUTPUT
     DYNPLTA TIME(0.,4.),FTB(-150000.,150000.)
     DYNPLTA TIME(0.,4.),DELN(-5.,5.)
     DYNPLTA TIME(0.,4.),TPREQ(0.,1.)
     DYNPLTA TIME(0.,4.),VXAP(0.,10.)
     OUTPLT VXAP,TH,FTB,FCH,FCHD,DELCH,DCH,CL,MUTM,MUTN,...
            FXTM,FXTN,FZTM,FZTN,FZGM,FZGN,YM,YN,DELN,FXGN,...
            FXENG,FZTF,FZTR,XNDD,X1DD,X2DD,TPREQ,VTCW,TH1
     PRINT X1,X2,XN,XM,X1D,X2D,XND,XMD,X1DD,X2DD,XNDD,XMDD,...
           Z1,Z2,ZN,ZM,Z1D,Z2D,ZND,ZMD,Z1DD,Z2DD,ZNDD,TPREQ,...
           TH1,TH1D,TH,THD,VTCW,VXN,VXM,DELN FXDR,FXTN,...
           FXTM,FXGN,FXT,FZTN,FZTM,FZGN,FCH  TB,DCH,FZGM,...
           FCHD,MUTN,MUTM,YM,YN
     END
     STOP

OUTPUT VARIABLE SEQUENCE
X1D0     XND0     XMD0     X2D0     Z1D0     ZND0     ZMD0     Z2D0     THD0     TH1D0
TH0      TH10     DELN0    DZN      FSCG     DXM      DXN      FZGN     YN0      FZGM
YM0      DZM      FZTM     ZM0      Z20      XM0      STUG     DXF      DXCH0    DZCH
HCG0     KTR      DYR      W1       FZTF     FZTR     ZR       KTF      ZF       Z10
ZCH      FZTN     ZN0      ZTB      XTB      X20      XN0      XCH      X10      XSTART
```

Figure A-1. CSMP Towing Program Listing (Sheet 5 of 6)

```
6       CONV    A       PI      I1      BTF     BTR     DS      STH     CTH
VN      YN      VM      YM      DELND   DELN    CTH1    STH1    Z1N     ZTBP
XTBP    X1N     DXCH    XCH     XTB     ZCH     ZTB     ALPHA   CATH1   Z1ND
XTBPD   X1ND    DELCHD  DELCH   DCH     FH      FTBH    FCHD    TERMM   DCHABS
FCHABS  FCH     FTBCH   FTB     FXTB    XLR     ZZ0004  ZZ0006  ZRRD    ZTRD
ZZ0005  ZRR     ZTR     FZTR    XLF     ZZ0001  ZZ0003  ZRFD    ZTFD    ZZ0002
ZRF     Z1F     FZTF    MUBPTV  VTOW    VTREL   VTLIM   MUTOW   FXDR    VTOWFR
THRUST  TP      FXENGB  ACC2    ACC1    TTD     TDUM2   TTC     TDUM1   TDUM
ACC     THTF    ACCEL   ZZ0007  ZZ0009  ZRND    ZTND    ZZ0008  ZRN     ZTN
FZTN    VXN     VXNREL  VXNLIM  MUTN    FXTN    ZZ0010  ZZ0012  ZRMD    ZTMD
ZZ0011  ZRM     ZTM     FZTM    MUBRAP  VXM     VXMREL  VXMLIM  MUTM    FXTM
DRAG    THRREQ  FXENG   FXT     X1DD    X1D     FZTB    Z1DD    Z1D     TERM3
TERM2   HCG     TERM1   TH1DD   TH1D    BHN     FHN     FAN     FZGN    KXN
BXN     FXGN    XNDD    XND     ZNDD    ZND     BHM     FHM     FAM     FZGM
ZMDD    ZMD     FXGM    X2DD    XMD     X2D     Z2DD    Z2D     LN      MYN
LM      MYM     THDD    THD     X1      Z1      XN      ZN      ZM      XM
X2      Z2      TH      TH1     CL      VXAP    STUF2   STUF1   STUFF   THRMAX
TPREQ   XMDD

 OUTPUTS    INPUTS    PARAMS  INTEGS + MEM BLKS  FORTRAN  DATA CDS
228(500)  655(1400)  98(400)  23+  0= 23(300)  227(600)     58

        ENDJ
```

Figure A-1. CSMP Towing Program Listing (Sheet 6 of 6)

TABLE A-1. CSMP PROGRAM INPUT DATA (SHEET 1 OF 5)

Parameter	Description
FINTIM	Maximum analysis time
OUTDEL	Output plot interval
PRDEL	Output print interval
DELT	Integration interval
XDOTIC	Initial airplane velocity
VO	Reference velocity for friction force calculations
W	Airplane weight
I	Airplane pitch inertia
CG	Center of gravity position, percent M.A.C.
LEMAC	Fuselage station of leading edge, mean aerodynamic chord
CBAR	Mean aerodynamic chord
WM	Unsprung weight of 2 main landing gears
WN	Unsprung weight of nose landing gear
FSM	Fuselage station of main landing gear
FSN	Fuselage station of nose landing gear
WLM	Water line of main gear trunnion
WLN	Water line of nose gear trunnion
WLCG	Water line of airplane center of gravity
LOM	Fully extended length of main gear, trunnion to axle
LON	Fully extended length of nose gear, trunnion to axle
RM	Free radius of main gear tires
RN	Free radius of nose gear tires
KTM	Linear stiffness of all main gear tires, both gears
KTN	Linear stiffness of all nose gear tires
BTM	Linear damping constant of all main gear tires, both gears
BTN	Linear damping constant of all nose gear tires
FAOM	Two times initial preload of main landing gear
FAON	Initial preload of nose landing gear

TABLE A-1. CSMP PROGRAM INPUT DATA (SHEET 2 OF 5)

Parameter	Description
FAAM	Two times ambient airload of main landing gear
FAAN	Ambient airload of nose landing gear
BMT	Two times the main gear hydraulic damping constant during extension
BMC	Two times the main gear hydraulic damping constant during compression
BNT	Nose gear hydraulic damping constant during extension
BNC	Nose gear hydraulic damping constant during compression
EM	Effective total strut cylinder length, main gear
EN	Effective total strut cylinder length, nose gear
ZETNOS	Critical damping ratio for nose gear fore-aft mode
W15	Tug weight, T-500S
I15	Tug pitch inertia, T-500S
HCGO5	Unloaded cg height above ground, T-500S tug
W18	Tug weight, T-800S
I18	Tug pitch inertia, T-800S
HCGO8	Unloaded cg height above ground, T-800S tug
DXF5	Horizontal distance from cg to forward tug tires, T-500S
DXR5	Horizontal distance from cg to rear tug tires, T-500S
DXCHO5	Horizontal distance from cg to towbar hitch, T-500S
DZCH5	Vertical distance from cg to towbar hitch, T-500S
DXF8	Horizontal distance from cg to forward tug tires, T-800S
DXR8	Horizontal distance from cg to rear tug tires, T-800S
DXCHO8	Horizontal distance from cg to towbar hitch, T-800S
DZCH8	Vertical distance from cg to towbar hitch, T-800S
BCH	Linear damping constant for cushioned hitch (T-500S tug only)
KTF5	Linear stiffness of all forward tug tires, T-500S
KTR5	Linear stiffness of all rear tug tires, T-500S

TABLE A-1. CSMP PROGRAM INPUT DATA (SHEET 3 OF 5)

Parameter	Description
BTF5	Linear damping constant for all forward tug tires, T-500S
BTR5	Linear damping constant for all rear tug tires, T-500S
KTF8	Linear stiffness of all forward tug tires, T-800S
KTR8	Linear stiffness of all rear tug tires, T-800S
BTF8	Linear damping constant for all forward tug tires, T-800S
BTR8	Linear damping constant for all rear tug tires, T-800S
LTB	Towbar length from hitch centerline to nose gear hookup centerline
DS5	One half of total deadspace or backlash at towbar/hitch joint, T-500S
DS8	One half of total deadspace or backlash at towbar/hitch joint, T-800S
MUMO	Basic rolling friction coefficient, main gear
MUNO	Basic rolling friction coefficient, nose gear
MUMV	Velocity-squared rolling friction coefficient, main gear
MUNV	Velocity-squared rolling friction coefficient, nose gear
MUTOWO	Basic rolling friction coefficient, tow vehicle
MUTOWV	Velocity-squared rolling friction coefficient, tow vehicle
KIP	Constant to convert AFGEN (HITCH) from kips to pounds
FL1	Flag defining which tug thrust-velocity curve is used
FL2	Flag defining which tug thrust-velocity curve is used
FL3	Flag defining which tug thrust-velocity curve is used
FL4	Flag defining which tug thrust-velocity curve is used
FL500	Flag for specifying use of complete tug thrust-velocity curve, T-500S
FL800	Flag for specifying use of complete tug thrust-velocity curve, T-800S
FWDREV	Flag for defining direction of tow, + = forward, - = reverse

TABLE A-1. CSMP PROGRAM INPUT DATA (SHEET 4 OF 5)

Parameter	Description
FLBRAP	Flag for using AFGEN (APBR) for airplane braking
FLBRTV	Flag for using AFGEN (TVBR) for tug braking
SLOPE	Runway slope in radians, positive uphill
MODE	1 specifies time history input of throttle position (AFGEN(THR))
	-1 specifies input of acceleration curve parameters
VFINAL	Tug/airplane final velocity, m.p.h.
TC	Acceleration curve input and dropoff ramp times
TD	Acceleration curve dwell time
TUG	Flag specifying which tow vehicle used in analysis
	TUG = 5 uses T-500 model
	TUG = 8 uses T-800 model
KHITCH	Linear stiffness of towbar/hitch, used only with TUG = 8
BHITCH	Linear damping of towbar/hitch, used only with TUG = 8
AFGEN APBR	Time-history input table of airplane braking coefficient
AFGEN TVBR	Time-history input table of tug braking coefficient
AFGEN THR	Time-history input table of non-dimensionalized throttle position
AFGEN KXNOSE	Table of nose gear fore-aft stiffness versus strut compression
AFGEN HITCH	Table of cushioned-hitch load-deflection curve (T-500S tug only)
AFGEN T1	Table of tug thrust (KIPS) versus tug velocity (MPH), T-500S, 1st gear
AFGEN T2	Table of tug thrust (KIPS) versus tug velocity (MPH), T-500S, 2nd gear
AFGEN T3	Table of tug thrust (KIPS) versus tug velocity (MPH), T-500S, 3rd gear
AFGEN T4	Table of tug thrust (KIPS) versus tug velocity (MPH), T-500S, 4th gear

TABLE A-1. CSMP PROGRAM INPUT DATA (SHEET 5 OF 5)

Parameter	Description
AFGEN T500	Table of tug thrust (KIPS) versus tug velocity (MPH), T-500S, all gears
AFGEN T800	Table of tug thrust (KIPS) versus tug velocity (MPH), T-800S, all gears

TABLE A-2. CSMP PROGRAM OUTPUT DATA (SHEET 1 OF 2)

Item	Description
X1, X1D, X1DD	Horizontal position, velocity, acceleration of tug cg
X2, X2D, X2DD	Horizontal position, velocity, acceleration of airplane cg
XN, XND, XNDD	Horizontal position, velocity, acceleration of nose gear unsprung mass
XM, XMD, XMDD	Horizontal position, velocity, acceleration of main gear unsprung mass
Z1, Z1D, Z1DD	Vertical position, velocity, acceleration of tug cg
Z2, Z2D, Z2DD	Vertical position, velocity, acceleration of airplane cg
ZN, ZND, ZNDD	Vertical position, velocity, acceleration of nose gear unsprung mass
ZM, ZMD, ZMDD	Vertical position, velocity, acceleration of main gear unsprung mass
TPREQ	Required non-dimensionalized throttle position of maintain specified acceleration input curve
TH1, TH1D	Tug pitch angle, velocity
TH, THD	Airplane pitch angle, velocity
VTOW	Tow vehicle velocity, M.P.H., ground axes
VXN	Nose gear unsprung mass forward velocity, ground axes
VXM	Main gear unsprung mass forward velocity, ground axes
DELN	Horizontal deflection of nose gear, positive aft
FXDR	Tow vehicle drag due to rolling friction
FXTN	Nose tire drag
FXTM	Main tire drag (2 gears)
FXGN	Horizontal load on nose gear
FXT	Net thrust load on tow vehicle (thrust-drag)
FZTN	Vertical nose tire load
FZTM	Vertical main tire load (2 gears)
FZGN	Vertical nose gear load
FZGM	Vertical main gear load (2 gears)
FCH	Horizontal load in Cushioned-Hitch
FTB	Towbar axial load

TABLE A-2. CSMP PROGRAM OUTPUT DATA (SHEET 2 OF 2)

Item	Description
DCH	Towbar axial deflection
FCHD	Cushioned-hitch damping force
MUTN	Friction coefficient for nose tires
MUTM	Friction coefficient for main tires
YM	Main gear strut compression
YN	Nose gear strut compression